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The economic and energy impacts of a UK export shock: comparing alternative modelling approaches

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Abstract

Achieving the targets for reducing greenhouse gas emissions set out in the UK Climate Change Act will require a significant transformation in the UK's energy system. At the same time, the government is pursuing a new UK Industrial Strategy, which aims to improve labour productivity, create high-quality jobs and boost exports across the UK. The economic and the energy systems in the UK are tightly linked and so policies adopted in one area will produce spillover effects to the other. To achieve the objectives set out in the two strategies it is therefore vital to understand how the policies in the energy system will affect economic development and vice versa. This study seeks to contribute to this by investigating how an increase in exports (a key pillar in the UK Industrial Strategy) could impact energy- and industrial policy. We address this question by systematically comparing the results of two types of energy-economy models of the UK, a computable general equilibrium model and a macroeconometric model. In terms of the implications of a successful export promotion strategy, the models agree that there is likely to be a beneficial impact on the economy, but an adverse impact on CO_2 emissions and energy intensity. This reveals the extent of any policy adjustment that would be required to maintain a given level of emissions and serves to emphasise the need to complement UK industrial policies with appropriate action on energy use and carbon emissions to meet statutory carbon targets set by the Climate Change Act (2008). Our second main conclusion is that there are advantages to having a diverse mix, or portfolio, of energy-economy models with each having comparative advantages depending on: prevailing circumstances (including the state of the economy); the time-period of interest and the nature of the policy question being addressed.

Key words: energy policy, industrial strategy, trade policy, energy-economy modelling, climate policy

JEL: C68, D58, Q43, Q48

1 Introduction

Achieving the targets for reducing greenhouse gas (GHG) emissions set out in the UK Climate Change Act will require a significant transformation in the UK's energy system. The UK government's plan for achieving its climate change targets is set out in the Clean Growth Strategy (HM Government, 2017a). As part of the 2032 pathway set out in the strategy, the UK government aims to reduce the GHG emissions intensity of the UK economy by 5% each year until 2032 and improve the energy productivity of business by 20% by 2030. Overall, the government expects that the 2032 pathway will reduce final energy consumption by 13% compared to baseline projections, which would amount to an approximate reduction of 11% compared to 2016.

At the same time, the government is pursuing an Industrial Strategy with the aim of improving labour productivity, creating well-paid and high quality jobs and increasing economic growth across all regions of the UK (HM Government, 2017b).

The economic and the energy systems in the UK are tightly linked and so the policies adopted in one area will produce spillover effects to the other (see e.g. Ross et al. 2018a; Royston et al., 2018). This interaction could produce potential synergies, but also possibly hinder efforts in each policy area. To achieve the objectives set out in the two strategies, it is therefore vital to understand how the suggested policies in the climate and energy field will impact economic development and vice versa.

This study seeks to contribute to this understanding by investigating how an increase in exports could impact emissions, and other socio-economic variables in the UK. A central interest in the present paper is therefore on the incremental change in emissions that is likely to arise from export policy actions alone. This identifies the potential additional challenge made to meeting the Government's emissions targets that is solely attributable to export policy. As in Ross et al. (2018a), we focus on an increase in exports, because 'encouraging trade' is a critical pillar of the Government's Industrial Strategy, as part of the ambition to be a more 'Global Britain' (HM Government, 2017b). Although 'trading more, not less' seems to be a key goal, precise policies or quantifiable measures are not explicitly stated[1]. Accordingly, for now we proxy the impact of a successful trade-enhancing policy by an exogenous (and costless) 5% increase, above the baseline, in international export demands across all sectors of the economy. This augments the analysis in Ross et al (2018a) by providing a systematic comparison with an ME model to highlight the differences and similarities between the approaches.

Secondly, to add further insight, we address this question by comparing and discussing the results of two very different types of energy-economy models. Currently, two dominant approaches to the system-wide analyses that seek to capture the interdependence of the economic and energy sub-systems are computable general equilibrium (CGE) and macroeconometric (ME) models. Both types of models are widely employed by governments, international agencies and research organisations, academics and private sector consultancies for the analysis of economic and/or energy policies and other disturbance to

[1] Although the recently published UK Export Strategy (HM Government, 2018) now sets a target to "raising exports as a proportion of GDP from 30% to 35%". We shall explore in future the system-wide implications of reaching this target. However, the Export Strategy currently does not provide detail on the precise policy instruments to be used.

the economic and/or energy sub-systems (see e.g. European Comission, 2016; HMRC, 2013; and Scottish Government 2016 for CGE models, and e.g. Dagoumas & Barker 2010; European Commission 2015 and OBR 2015 for applications of ME model).

The applications of these models span a wide range of energy and economic policies. For example, Allan et al., (2007) analyse the impacts of increased efficiency in the industrial use of energy. Figus et al. (2017) identify the impacts of energy efficiency programmes on households. Lecca et al. (2014a) identify total energy rebound effects of improvements in household energy efficiency. The European Commission (2015) analyses policies directed at the promotion of energy efficiency in production or consumption. Ekins et al. (2012) consider the imposition of environmental and other taxes, and Ross et al. (2018a,c,e) consider the impact of other fiscal and industrial policy initiatives.

Given that the interdependence of the energy and economic sub-systems is central to these models, they are well suited to focus on the spillover effects both from economic policies to the energy system and vice versa. This interdependence is often crucial to an in-depth understanding of any given disturbance. For example, the likely impact of energy efficiency policies are transmitted, in part, through induced relative price changes and wider economic responses, which largely govern the extent of "rebound" (Hanley et al. 2009).

Assessing the impact of an increase in exports on energy use, for example, is strongly dependent on the economic assumptions and type of model that is used. The formulation of policy can therefore benefit from taking into account the results of both ME and CGE models, exploiting their complementary strengths. For example, this is routinely done in the provision of evidence to the European Commission (e.g. European Commission 2015). Despite the benefits that the comparison of CGE and ME models can bring, it has rarely been applied to policy making in the UK.

The comparison of the two model types in this study therefore serves two important functions. First, it allows us to provide more robust evidence as it takes into account some of the uncertainty that is associated with the structure of any single model. Second, it also allows us to discuss the comparative strengths and weaknesses of the two modelling approaches. As a result, we hope that this study will be a useful resource to the research and policy community by enhancing the understanding of both modelling approaches and how they can be used together.

While there is a very wide range of both CGE and ME energy-economy models, we focus here on the two models that have been used for analysis within the UK Energy Research Centre (UKERC) research programme; namely UK-ENVI, a computable general equilibrium economy-energy- environment model of the UK, and the UK MAcroeconometric and Resource COnsumption (MARCO-UK) model, a ME energy-economy model of the UK (Sakai et al. 2019). We set up the UK-ENVI and MARCO-UK models in an analogous way that allows for a systematic comparison of the system-wide impacts of a demand-side disturbance, an exogenous increase in exports, across the two models. However, when making model comparisons we emphasise where their characteristics are representative of the wider class of ME and CGE models (and also where they are not), so that our analysis has relevance beyond the narrow comparison of these two specific models.

In Section 2 we provide a brief comparative overview of UK-ENVI and MARCO-UK and the wider class of models to which each belongs. Here we emphasise the differences – and similarities in some instances – in the underlying visions of the UK macro-economy that are embodied in both models, since these inform to a degree the simulation properties of the models in a way that is perhaps not always obvious to non-modellers. We outline differences between the model types in terms of model: theoretical basis; specification; parameterisation; solution and simulation. In Section 3 we set out our modelling strategy, which seeks to ensure that the impact of a successful UK export promotion strategy is simulated in a similar way in both models to facilitate comparison. Section 4 outlines the structure of both models and explains how they are parameterised (and the data required to facilitate this process). In Section 5 we summarise the simulation results from each model initially separately, then compare them in some detail, drawing attention to similarities and differences in Section 6. Section 7 provides brief conclusions.

2 Comparing CGE and ME Energy-Economy Models

There is considerable variability even among CGE and ME models, but each approach has some fairly general distinguishing characteristics. In this section, we set out a brief comparison of the versions of ME and CGE models that have been used within the UKERC consortium to explore energy-economy issues.

2.1 Theoretical basis

2.1.1 Brief overview of two approaches to macroeconomic theory

It is important to begin with an appreciation of the underlying vision of the UK macro-economy embodied within MEs and CGEs. UK-ENVI is a CGE model drawing on neoclassical economic theory. Archetypal CGE models are developed from well-specified, micro-economic theory in which behavioural relationships are derived from optimising agents and in which prices "clear" markets continuously so that resources are optimally employed. However, these assumptions are often relaxed in the current generation of CGE models (including UK-ENVI) to allow for labour market imperfections and involuntary unemployment, which implies that "equilibria" are not necessarily "optimal" in any sense (see e.g. Partridge & Rickman, 2010). CGEs have typically been regarded as reflecting an ultra-neoclassical view of the world in which demand may not matter much (if at all) and supply influences are expected to dominate in terms of affecting the aggregate real economy. However, in UK-ENVI, both demand and supply typically matter for the determination of output and employment.

CGE models rely strongly on theoretical assumptions with regard to the behavioural functions and also assume that the economy as a whole is in equilibrium in the base year. On the one hand, these assumptions allow the construction of detailed models without large amounts of historical time-series data, as many parameters in the model can be derived from the calibration to a single base year (although it should be noted that some parameters in CGE models are also estimated econometrically). In addition, the stronger alignment with economic theory can provide CGEs with an advantage in terms of interpreting model results. On the other hand, CGE models have sometimes been subject to the "black box" criticism: the models are so complex that it is difficult to understand what is going on inside them. UK-

ENVI seeks to avoid this outcome by: allowing numerous “switches” in the model that can curtail elements of endogeneity to allow tracking the source of results that initially appear surprising; incremental model augmentation, and sensitivity analysis (with respect to behavioural functions as well as parameter values). Traditionally, most CGE models were static in nature, but increasingly they incorporate dynamics. UK-ENVI is a dynamic model that generates multiperiod simulations, which track the adjustment paths of all endogenous variables in the model. Accordingly, it can be used directly to compare entire adjustment paths, as well as, of course, impact and long-run effects, with dynamic ME models

MARCO-UK is a ME model based (as is common) on post-Keynesian economic theory, where agent behaviour is not based on optimisation but is instead determined from econometric equations based on historical data. The economy is conceptualised as a non-equilibrium system in the sense that markets are often not efficient and that prices and quantities do not adjust to optimal, market-clearing levels (Barker et al. 2012; Lavoie 2014a). Instead, post-Keynesians consider that prices are set by firms using some form of mark-up pricing, although it is acknowledged that the interplay of supply and demand can impact prices in some markets (Lavoie 2014b). It is assumed that in most circumstances not all resources are optimally used and that spare capacity exists in the economy, which allows economic growth to be demand led both in the short and long run (Fontana & Sawyer 2016). In the short run, production adjusts to increased demand through the increase in the utilisation of capacity, while in the long run the total capacity of the economy adjusts to demand through increased levels of investment (Taylor et al. 2016). As a result, economic production is not constrained by supply-side factors in the MARCO-UK model. Post-Keynesian theory recognises that supply-side factors, especially insufficient labour supply, can constrain production in unusual circumstances. Such constraints are not explicitly built into the MARCO-UK model, but we take them into account by rejecting any scenarios in which employment outstrips the available labour force[2].

It should also be noted, that the theoretical assumptions underlying CGE and ME models are often contested; for example, there exist conflicting theories of transactor behaviour depending on circumstances. The modeller’s choices here may have a significant impact on model behaviour (one motivation for the use of a range of UK-ENVI configurations). So, for example, behavioural economists have found evidence of significant and systematic deviations from rationality that would affect the appropriate specification of transactors’ behavioural functions. The post-Keynesian theory underlying ME models generally rejects neoclassical microeconomic assumptions describing, rational, utility or profit-maximising agents and also suggest that macroeconomic dynamics cannot be derived solely from definitions of microeconomic behaviour (Lavoie 2014, p.17). Instead ME models rely on behavioural equations that are statistically estimated from historic time-series data. The specification such equations is not only based on economic theory but is also influenced by considerations of statistical significance and data availability, a practice that is sometimes being criticised as being ad hoc. In addition, the use of statistics and historical time series implies the significant assumption that statistical relationships identified in past data are also relevant in the future. This assumption constitutes an important source of uncertainty for ME

[2] Employment never exceeded the available labour force in any scenario conducted with the MARCO-UK model for this study (see Appendices A and B for information on unemployment in all scenarios conducted).

model projections into the future, which increases with distance from the current time. This is a challenge inherent to all empirical modelling.

The underlying macroeconomic vision in any model has a significant impact on its properties and the predicted impact of different policy interventions. Two key areas of divergence are the labour and the capital market, which are discussed below.

2.1.2 Labour market

Under limiting neoclassical assumptions, it is assumed that wages always adjust to ensure full employment and the optimal use of all available labour. One configuration of the labour market treatment in UK-ENVI corresponds rather closely to this neoclassical extreme, namely that with Exogenous Labour Supply (ELS), in which employment is fixed. However, UK-ENVI is atypical of CGEs in general in that it seeks to accommodate a range of alternative visions of the labour market and the macro-economy on the grounds that, in general, the evidence does not provide compelling support for any one vision, although it clearly favours some visions over others.

Three further characterisations of the labour market are captured within UK-ENVI. The default version of the model incorporates a wage curve or bargained real wage function (BRW). The BRW version of UK-ENVI is associated with a less markedly neoclassical macroeconomic perspective than ELS, because it relaxes the strict labour supply constraint associated with ELS, so that demand plays a greater role in determining economic activity. Furthermore, we allow for fixed nominal (FNW) or real wages (FRW), which some would argue might better characterise the behaviour of the UK economy over the last decade. These variants of UK-ENVI emulate the behaviour of Keynesian models over the long run for demand disturbances, because they impact solely on quantities, with no impact on wages or prices. As will become clear, however, within UK-ENVI even fix-wage models are subject to supply constraints in the short run due to the fixity of capital stocks.

In fact, the very widespread support for the empirical relevance of wage curves has led us typically to adopt the BRW configuration of the labour market as our default. UK wage behaviour over the last decade does, however, suggest the merit of seriously considering the impact of fix-wage models (FNW and FRW). These may ultimately prove to be a “temporary” deviation prior to a return to “normal” wage bargaining behaviour, but since a decade has passed since the onset of the Great Recession, that deviation has been very long lasting. We do not believe that the empirical evidence supports the ELS model, but it serves as a useful benchmark of a continuous full-employment model that characterises many national CGE models.

While the amount of available labour is a key constraint determining economic output under the extreme neoclassical assumption, this is not the case for the MARCO-UK model (nor for the other UK-ENVI models). In MARCO-UK the level of employment is determined by the level of economic output (which is driven by demand) and by the availability of other production factors, capital and energy, which mediate the relationship between employment and economic output. As outlined above, full employment is not fully achieved and there is the capacity to absorb an increase in labour demand so that there are no supply constraints. In addition, the labour force available for employment is also somewhat elastic to increases in economic output, in line with historical relationships. Real hourly wages in MARCO-UK are in turn determined by demand for labour and unemployment. The determination of wages in the MARCO-UK model is therefore not dissimilar to the bargained real wage function employed in UK-ENVI.

2.1.3 Capital market and crowding out

A second feature that is often discussed as a key difference between CGE and ME models is the treatment of capital markets and the crowding out of investment (Pollitt & Mercure 2018). However, this difference is not relevant for our current study because neither UK-ENVI nor MARCO-UK feature detailed treatments of capital markets.

As is common in CGEs, UK-ENVI has no financial sector, and the interest rate is typically exogenous. While financial sectors can be incorporated into CGEs, this is comparatively unusual. The exogeneity of the interest rate is a simplification that is strictly only valid in circumstances where the Central Bank is committed to maintaining it at that level, or where there is a liquidity trap, with interest rates are so low that market participants expect them to rise (and bond prices to fall) and prefer to hold cash (rather than bonds). This may be a reasonable characterisation of monetary policy in the UK's recent past. However, in future work we shall relax this assumption. Accordingly, there is no financial "crowding out" within UK-ENVI as configured here; any crowding out that does occur is attributable solely to supply-side constraints.

Similarly, the treatment of the financial sector in the current version of MARCO-UK is limited. The link between the financial and the real economy is largely implicit and relies on the assumption that investment is not constrained by the financial markets. This assumption is not uncommon in ME models (Pollitt & Mercure 2018). MARCO-UK does feature some representation of the money supply and interest rates that determines the general price level. However, the econometric equations estimated for the model assign those monetary variables only a very limited influence on the real economy.

In the wake of the financial crisis the close link between the financial system and the real economy has received increasing attention and the lack of financial sector representation in both CGE and ME models used for economy-environment analysis has attracted criticism (Pollitt & Mercure 2018; Rezai & Stagl 2016). This lack of adequate financial representation is a limitation of both the models employed in this study and should be kept in mind when interpreting the results.

The development of ME and CGE models can typically be regarded as occurring in four main stages: specification; parameterisation; solution and simulation. We consider each stage in turn and discuss the differences among modelling approaches.

2.2 Model specification

The specification of system-wide models must in part reflect the purposes of the model and also the vision of the economic – and here the energy – system that underlies it.

2.2.1 Sectoral structure and energy

The choice of model structure can significantly affect results. In the present case, it is essential to choose a structure that allows the capture of energy-economy system interdependencies; both UK-ENVI and MARCO-UK do that, though in rather different ways. The different structures, of course, constrain the kinds of policy questions that can be addressed in each model.

In the present application, UK-ENVI contains 30 sectors, but the precise number and definition of sectors can be varied depending on the question of interest, with full sectoral disaggregation at 94 sectors following the UK disaggregation of economic accounts. The energy system is represented by energy-producing sectors that produce energy as an input into the production of other sectors.

Energy is treated in UK-ENVI as an intermediate input in the sectoral production hierarchy, which has a KLEM (capital-labour-energy- materials) structure. However, the efficiency of energy (and indeed other inputs) can be varied (typically exogenously). The analysis of such changes in energy efficiency in production (e.g. Allan et al., 2007) and in consumption (e.g. Lecca et al., 2014a; Figus et al., 2017) underlies system-wide analyses of rebound effects (e.g. Turner 2009).[3] Energy demands within each sector, like the demands for labour and capital, are derived demands, and domestic energy prices are typically determined by the interaction of the sectors that demand energy and those that supply it (and exogenous external prices).

The current version of MARCO-UK is highly aggregated. The overall dynamics of output, employment and capital stocks are determined at the aggregate level of the whole economy. However, the aggregate output is then broken down into two sectors, an industrial and a non-industrial sector, and final energy consumption is determined at this disaggregated level. The nature of ME models as a system of simultaneous econometric equations makes it a challenging task to increase the number of sectors as the complexity of the model increases quickly, which can make it difficult to achieve stable and coherent model behaviours. However, further disaggregation is planned in future versions of MARCO-UK.

The treatment of energy is a key innovative feature of MARCO-UK. It is the first ME model that explicitly includes useful exergy as a production factor. Useful exergy represents the energy that is actually used in the economy, such as the movement of a car or the light emitted by a light bulb. It is the expression of energy use that is closest to the total use of energy services but can still be measured in energy units (Sousa et al. 2017). It has been shown that useful exergy is more closely related to measures of economic output than other measures of energy use (Ayres & Warr 2005; Santos et al. 2016). Useful exergy use is then linked to the use of final energy carriers via an endogenous efficiency variable, representing the technical transformation efficiency from final energy to useful exergy. Drawing on theory developed by Ayres et al. (2003) this efficiency is an important influence on the evolution of the UK economy in the MARCO-UK model (Sakai et al. 2019).

2.2.2 Treatment of time

CGE models often make a conceptual distinction between two time periods. These time periods include the short run, which denotes an equilibrium with fixed capital stocks, and the long run, which denotes the point in time where capital stocks in each sector are fully

[3] The analyses use the concept of efficiency units of energy, which may allow a link to the notion of exergy.

adjusted to their desired levels.[4] UK-ENVI can be used in comparative static mode to determine short-run and long-run equilibria, but it is typically run in full dynamic mode, in which the adjustment paths from short- to long-run equilibria are tracked. This traces the consequences of any induced changes in investment expenditure on sectoral capital stocks and productive capacity. A stimulus to demand, for example, tends to increase rental rates (profits) and so stimulate investment expenditures. However, this leads to increases in capital stocks and production, which ultimately lowers profitability to normal levels again, but with capacity permanently increased.

ME models, such as MARCO-UK, do not make such a conceptual distinction. MARCO-UK does not optimise any variable and hence the model does not feature an equilibrium produced by the optimising behaviour of transactors and the adjustment of prices at any point in time (although it is assumed that aggregate supply is equal to aggregate demand in every time period according to definitions given by the System of National Accounts). Instead, every time period (one year) is treated the same and the model is solved for each year based on the econometric equations and current and previous values of the model variables. This means that the model variables are continuously changing, generally producing a growing economy. The growth paths of the economy in the model are, in most circumstances, smooth and stable. However, if shocks are applied to the model, such as the export shock applied in our study, the model often shows a period of less stable, fluctuating dynamics, before it settles again unto a stable growth trajectory. Stable trajectories in ME models are also sometimes referred to as an 'equilibrium' but we do not use this terminology to avoid confusion with the very different equilibria produced by CGE models. Overall MARCO-UK covers the time period from 1971 to 2050, with 1971-2013 as the time period over which the econometric equations are fitted, and 2014-2050 presenting a forward projection of the model.

2.2.3 Expectations formation

MARCO-UK assumes that expectations are myopic. The version of UK-ENVI used in this study also relies on myopic assumptions to facilitate better comparability of model results. This means that the group of agents in the models make decisions only based on the current values of model variables) without looking forward into the future. This is a common assumption in post-Keynesian economic theory, but it represents a significant deviation from the ultra-rational neoclassical specification, characterised by intertemporal optimisation of households (determining consumption) and firms (investment) under perfect foresight (or rational expectations in the stochastic case). Although not implemented in this study, UK-ENVI can be run under perfect foresight assumptions, with forward-looking consumption and investment behaviour, as well as under myopic assumptions (Lecca et al, 2013). This typically has an impact on time paths of adjustment, but not on long-run results. This option has the advantage of identifying the consequences of eliminating the systematic errors associated with transactor groups that have myopic expectations and allowing an analysis of alternative expectations formation assumptions.

[4] The definition of the short run captures the idea that it takes time for investment expenditures to augment the capital stock. The demand effects of the increased investment spending are felt immediately, but capital stocks only begin to adjust in the following period.

2.3 Model parameterisation

UK-ENVI, like many CGEs, is calibrated to a base year Social Accounting Matrix (SAM)[5] that is constructed around data from UK National Accounts. Given the values of certain key parameters (e.g. substitution and demand elasticities, which may themselves be estimated econometrically), the remaining parameters are determined by reconciling model equations with the SAM database. In effect, the strong theoretical assumptions on agent behaviours and the assumption that the economy is in equilibrium in the base year allows the construction of a very detailed model, without the need for large amounts of time series data. It also aids the interpretation of the model results. Econometric estimation of full CGEs has not yet proved feasible, given the huge data requirements and technical difficulties estimating such large systems.

MARCO-UK, in line with other ME models, contains two types of equations (identities and econometric equations) with each type accounting for about half the number of equations. While identities are generally derived from accounting relationships, econometric equations are parameterised using econometric methods drawing on time series data. The econometric estimation of the MARCO-UK model equations is built on a data set containing time-series of more than 50 variables covering the years 1971 to 2013. This use of time series data to check on model performance is a major strength of ME models (and also means that they more readily facilitate forecasting). It also allows for the underlying behavioural (and other) assumptions in the model to be tested and adapted in line with empirical results, although this trait is not unique to ME models. However, the data intensity of the ME method also presents constraints on the complexity of the models that can be developed and can make it more difficult to interpret model results.

2.4 Model solution

While the non-linearity of CGEs had at one point appeared to present a major technical hurdle, their solution is now routine. UK-ENVI is coded in GAMS and is solved using CONOPT/MINOS (both general purpose nonlinear programming solvers).

The MARCO-UK model consists of a system of simultaneous, linear equations. It is dynamically solved for each time period using the Gauss-Seidel iterative method included in the EViews econometric software (Startz, 2015).

2.5 Model simulation

MARCO-UK can be used for both ex-post and ex-ante dynamic simulation. However, in the present exercise, as we explain in the next section of the paper, we use both MARCO-UK and UK-ENVI to isolate the ex-ante impact of a simple stimulus to exports so that we can directly compare model results in as straightforward a manner as possible.

[5] See Emonts-Holley et al. (2014) for a detailed discussion of the computation process

Currently, neither MARCO-UK nor UK-ENVI are used for forecasting. In principle, CGEs could be used for this purpose, but in practice rarely are. ME models are more suited to develop short-term forecasts.

3 Simulation strategy

We use a simulation of both models to provide a systematic comparison of the system-wide impacts of a demand side disturbance, an exogenous increase in exports, across the two models (model specifications are given in Section 4).

We limit the current analysis to a demand-side disturbance because we want to focus on the comparison of the two models without adding the further complication of multiple scenarios. However, in the future we seek to provide additional comparisons where we shall also consider the implications of supply-side disturbances such as labour productivity improvements and increases in energy efficiency in both production and consumption. This will provide a more complete overview of the two models.

3.1 Implementing the export shock in UK-ENVI and MARCO-UK

To simulate the impact of an export shock we apply a 5% increase in exports to both models and, for each model, obtain the economic impacts by comparing the results of the scenario with the respective models' baseline scenario. We set up the UK-ENVI and MARCO-UK models up in a similar way, but the structures of the models mean that the scenario has to be implemented in different ways.

The UK-ENVI model is assumed to be in equilibrium calibrated to the base year, so that the baseline scenario simply recreates the baseline values over time. Given the adoption of myopic expectations here, the stimulus to exports is, of course, unanticipated. A permanent export shock, equivalent to 5% of exports in the base year, is then introduced to the model.

In UK-ENVI, the shock is implemented by adding the exogenous shock on top of the endogenously calculated exports in the model in every single year. The resultant stimulus to demand typically puts upward pressure on prices, and this loss of competitiveness can reduce the endogenous component of exports calculated in the model. This means that, depending on the treatment of the labour market, total exports (including endogenous component and exogenous shock), might not increase by 5%. To observe the adjustment of all the economic variables through time, simulations are run for 50 years, the adjustment period to the long run varies but is typically complete within 7-12 years.

In contrast, the baseline scenario of the MARCO-UK model represents a forward projection of the growth path of the UK economy from 2014 to 2050 based on the best-fit model obtained from the data covering 1971 to 2013 and given exogenous variables (e.g. population). The export shock is implemented by making exports in the model exogenous, and increasing them by 5% compared to the baseline for each year from 2014 onwards. This means that, by way of construction, the 5% increase in exports is always achieved.

3.2 Assumptions about fiscal policy

We make the assumptions about fiscal policy as similar as possible in the two models, although some limits are imposed by the different structure. For fiscal policy in UK-ENVI we simply assume that government expenditure is fixed in real terms. In the case of an expansionary response to the export stimulus, this implies that additional government revenues are simply being accumulated, for example, to retire debt (which has no further feedback because of our monetary policy assumptions). However, we do indicate the likely consequences of recycling the additional tax revenues into current government spending (which, for simplicity we assume to have no supply-side impacts) within UK-ENVI, to give some idea of the quantitative importance of this difference in model set-up, which we report in Ross et al. (2018a). In MARCO-UK, government expenditure is exogenous and is simply kept the same in the baseline and export shock scenarios. The current version of MARCO-UK does not feature a detailed representation of taxes and other government revenues. Instead, it is simply assumed that government income increases in proportion with GDP. The differences in the treatment of government income can lead to differences in the wider results as it determines how much of any extra income generated from the export shock is recycled into further spending and economic activity. However, a sensitivity analysis conducted for the MARCO-UK model suggests that the specification of government income only has a limited influence on the wider results of the model.[6]

As such, we provide a comparative analysis of the two models, UK-ENVI and MARCO-UK, whilst also outlining policy relevant implications of the likely system-wide impacts of UK trade-enhancing industrial policies. Notably, in the case of the UK-ENVI model, these results are explored and discussed in much fuller detail in Ross et al. (2018a).

The following section outlines the key features of the UK-ENVI and the MARCO-UK model.

4 Model and data

4.1 UK-ENVI model

The UK-ENVI model was purpose built to capture the interdependence of the energy and non-energy sub-systems of the UK. Versions of this model have been employed, for example, to analyse the impacts of increased efficiency in the industrial use of energy (Allan et al., 2007), identify the impacts of energy efficiency programmes on households (Figus et al., 2017), analyse the impacts of non-energy policies on key elements of the energy system (Ross et al., 2018a), and to identify total energy rebound effects of improvements in household energy efficiency (Lecca et al., 2014a).

Households' consumption and firms' investment are governed by intertemporal optimisation. In the following sections we provide a description of the main characteristics of the model,

[6] We implemented an alternative export scenario in MARCO-UK in which government expenditure was fixed at baseline levels and did not increase in line with GDP. This produced results only marginally different from the ones presented here (e.g. GPD increase of 2.61% against 2.64%). See Appendix B for further details on the results of this alternative scenario.

with a particular emphasis on the linkages between the economic and energy sub-sectors. We provide a full mathematical description of the model in Ross et al. (2018a).

4.1.1 Consumption and trade

We model the consumption decision of five representative households *h* as follows:

$$C_{h,t} = YNG_{h,t} - SAV_{h,t} - HTAX_{h,t} - CTAX_{h,t} \tag{1}$$

where total consumption *C* is a function of income *YNG*, savings *SAV*, income taxes *HTAX*, and taxes on consumption *CTAX*.

Consumption is modelled to reflect the behaviour of a representative household that maximises its discounted intertemporal utility, subject to a lifetime wealth constraint. The solution of the household optimisation problem gives the optimal time path for consumption of the bundle of goods C. To capture information about household energy consumption, consumption is allocated within each period and between energy goods and non-energy and transport goods and services (including fuel use in personal transportation) as indicated in the top level of the consumption structure shown in Figure 1. This choice is made in accordance with the following constant elasticity of substitution (CES) function:

$$C_{h,t} = \left[\delta_h^E \left(EC_{h,t}\right)^{\frac{\varepsilon_h - 1}{\varepsilon_h}} + (1 - \delta_h^E) TNEC_{h,t}{}^{\frac{\varepsilon_h - 1}{\varepsilon_h}}\right]^{-\frac{\varepsilon_h}{\varepsilon_h - 1}} \tag{2}$$

where ε is the elasticity of substitution in consumption, and measures the extent to which consumers substitute residential energy consumption, EC, for non-energy and transport consumption, TNEC, δ ϵ (0,1) is the share parameter. For simplicity (and in the absence of better information), in all households we impose a value, 0.61, for ε, which is the long-run elasticity of substitution between energy and non-energy estimated by Lecca et al. (2014a). The consumption of residential energy includes electricity, gas and coal, as shown in Figure 1, although coal represents less than 0.01% of total household energy consumption. Within the energy bundle, given that we do not focus on inter-fuel substitution in the analysis below, we impose a small but positive elasticity of 0.2.

Moreover, we assume that the individual can consume goods produced both domestically and imported, where imports are combined with domestic goods under the Armington assumption of imperfect substitution (Armington, 1969):

$$QH_{i,t} = \gamma_i^f \cdot \left[\delta_i^{hir} \cdot QHIR_{i,t}^{\rho_i^A} + \delta_i^{hm} \cdot QHM_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{3}$$

where QH is total household consumption by sectors, QHIR is consumption of locally produced goods, QHM is consumption of imported goods, and the *i* subscript represents the sector. With the price of imports being exogenous, substitution between imported and domestically produced goods depends on variations of national prices.

It must be noted that the Armington assumption has implications for the decisions of both producers and consumers. The choice over imported or domestic inputs for firms depends on their relative prices, as well as the Armington elasticity. Similarly, consumers choose over imported and domestic goods depending on relative prices and the Armington elasticity. Intermediate purchases in each industry are modelled as the demand for a composite commodity with fixed (Leontief) coefficients (as outlined in the following section in more detail). These are substitutable for imported commodities via an Armington link, which is sensitive to relative prices. Given the importance of the Armington elasticities to trade, Ross et al. (2018a) identify the implications of different values of these elasticities in a sensitivity analysis.

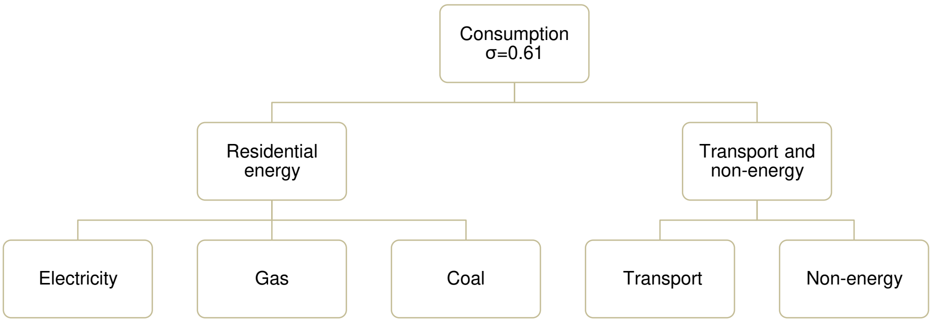

Figure 1: The structure of consumption in UK-ENVI

4.1.2 Production and investment

The production structure of each of the thirty production sectors is characterised by a capital, labour, energy and materials (KLEM) nested CES function. As we show in Figure 2, the combination of labour and capital forms value added, while energy and materials form intermediate inputs. In turn, the combination of intermediates and value added forms total output in each sector.

Following Hayashi (1982), we derive the optimal time path of investment by maximising the value of firms, V_t, subject to a capital accumulation function $\dot{K}_t$, so that:

$$Max\ V_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[\pi_t - I_t\big(1 + g(x_t)\big)\right] \text{ subject to:} \dot{K}_t = I_t - \delta K_t \qquad (4)$$

where π_t, is the firm's profit, I_t, is private investment, $g(x_t)$ is the adjustment cost function with $x_t = I_t/K_t$ and δ is depreciation rate. The solution of the optimisation problem gives us the law of motion of the shadow price of capital, λ_t, and the adjusted Tobin's q time path of investment (Hayashi, 1982).

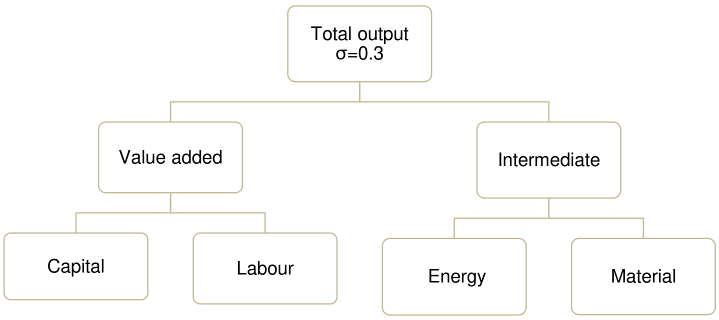

Figure 2: The structure of production in UK-ENVI

4.1.3 The labour market

Our default model specification embodies a wage curve, which is an inverse relation between the rate of unemployment and the real wage. Wages are thereby determined within the UK in an imperfectly competitive context, according to the following bargained real wage (BRW) specification:

$$\ln\left[\frac{wb_t}{cpi_t}\right] = \varphi - \epsilon \ln(u_t) \qquad \text{where } wb_t = \frac{w_t}{1+\bar{\tau}_t} \tag{5}$$

where wb_t/cpi_t is the real take home wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment u_t, and $\bar{\tau}_t$ is the income tax rate. So here the real consumption (after tax) wage is negatively related to the rate of unemployment (Blanchflower & Oswald, 2005), which is an indicator of workers' bargaining power.

The working population is assumed to be fixed and exogenous. This model implies the presence of involuntary unemployment (with BRW lying above the competitive supply curve for labour).

While there is compelling international evidence in favour of our default BRW specification, we consider a number of alternative labour market closures, to reflect alternative visions of how the UK labour market operates. We do this for two main reasons. First, there exists genuine uncertainty about the way that the aggregate UK labour market currently operates and there has been considerable controversy surrounding the issue (e.g. Bell & Blanchflower, 2018). Secondly, we wish to check the extent to which spillovers from economic policies to e.g. the energy system, vary with alternative visions of UK labour market behaviour. This allows us, as far as is practical within the UK-ENVI model framework, to check that our conclusions are robust with respect to the choice of any particular model of the UK labour market.

One alternative version that is often made by conventional CGEs of national economies is one where an entirely exogenous labour supply is assumed (with both population and the participation rate invariant): that is, labour supply exhibits a zero elasticity with respect to the real wage. This exogenous labour supply (ELS) vision of the market implies that employment is fixed.

$$L^s = \overline{L^s} \tag{6}$$

This vision of the labour market implies that the UK operates under a very tight supply constraint. Note that, in the short run, capital is fixed in each sector in this case, and so too is value-added. Aggregate GDP can only vary in response to disturbances that alter the allocation of activity across sectors. Furthermore, employment is effectively fixed even in the longer-term, and is, of course, invariant to any change in demand, although capital stocks can adjust in response to changes in rental rates [7].

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[7] In the longer-term population and labour supply can, of course, increase through natural population growth. For simplicity we abstract from that here. Migration flows could also alter labour supply, but we assume that net migration is zero here. However, the fixed real wage model emulates many of the features of a system with endogenous (flow) migration.

Some take the view that workers in the UK bargain to maintain their real wage - 'real wage resistance' - that results in a fixed real wage (FRW) model (at least in the absence of productivity growth). This model implies:

$$\frac{w_t}{cpi_t} = \frac{w_{t=0}}{cpi_{t=0}} \tag{7}$$

This case effectively implies an infinitely elastic supply of labour over the relevant range. In stark contrast to the ELS case, here the real wage is fixed, and any demand disturbances will be reflected only in employment changes (over a range).

The ELS and FRW cases represent limiting cases of the responsiveness of the effective supply of labour to the real consumption wage, with elasticities of zero and infinity respectively. The BRW case represents an intermediate case in which the effective (bargaining-determined) level of employment varies positively with the real consumption wage.

While these cases provide a useful range of alternative visions of the UK labour market, recent experience casts some doubt on the current relevance of the BRW or FRW hypotheses, since real wages have been falling despite a fall in the unemployment rate. There is clearly some evidence of a degree of nominal wage inflexibility. Here we illustrate the likely implications of this by exploring the limiting case of a fixed nominal wage (FNW):

$$w_t = w_{t=0} \tag{8}$$

4.1.4 Government

The Government in UK-ENVI collects taxes and spends the revenue on a range of economic activities which are treated here as public consumption. The Government operates according to the following budget constraint where the government budget is given by government income minus expenditure:

$$GOVBAL_t = GY_t - \overline{GEXP_t} \quad \text{where } GY_t = d_g KY_t + IBT_t + \bar{\tau}_t \cdot LY_t + \overline{FE}_t \tag{9}$$

where *GOVBAL* is the government budget which is equal to the difference between government income *GY,* and government spending *GEXP.* GY is given by the share d_g of capital income *KY* that is transferred to the Government, Indirect business taxes, *IBT,* revenues from labour income *LY* at the rate τ [8], and foreign remittance FE.

Ross et al. (2018a) illustrate the consequences of this assumption, and impose a public sector budget constraint as an element of a sensitivity analysis. In that analysis it is assumed that the Government absorbs the budgetary impacts of any change in the economy by adjusting expenditure and keeping household income tax rates fixed[9].

[8] Note that the income tax rate τ is fixed by default.

[9] We do not explore the consequences of varying tax rates here since this generates complex supply-side responses. We shall explore this in a subsequent analysis.

4.1.5 Dataset and income disaggregation and energy use

To calibrate the model we follow a common procedure for dynamic CGE models assuming that the economy is initially in steady state equilibrium (Adams & Higgs, 1990). We calibrate the model using information from the UK Social Accounting Matrix (SAM) for 2010.[10]

The UK-ENVI model has 30 separate production sectors, including the main energy supply industries that encompass the supply of coal, refined oil, gas and electricity[11]. We also identify the transactions of UK households (by income quintile), the UK Government, imports, exports and transfers to and from the rest of the World (ROW).

The SAM constitutes the core dataset of the UK-ENVI model. However other parameter values are required to inform the model. These often specify technical or behavioural relationships, such as production and consumption function substitution and share parameters. Such parameters are either exogenously imposed, based on econometric estimation where available, or determined through the calibration process. Base year industrial territorial CO2 emissions are calculated, and linked to the CGE sectoral primary fuel use according to Allan et al., (2018). This essentially converts ONS data on sectoral physical use of energy to CO2 using UK emissions factors. From this, a proportioned emission factor for each of the three primary fuels (coal, oil and gas) is calculated for each sector to obtain sectoral base year emissions. To determine the emissions resulting from changes in the economy, simulations are run using the CGE model, which give the sectoral changes in the use of each of the primary fuels. With these changes, the new emissions are calculated. While substitutability among fuel uses is feasible, substitution in favour of renewables is not accommodated within the version of UK-ENVI used here. However, the focus is on the effects that are entirely attributable to export promotion *per se*. Of course, in practice these will operate in combination with other policies, including those designed to encourage substitution of renewables in electricity production. We have explored the impact of the introduction of renewable technologies in, for example, Allan et al. (2008) and Lecca et al. (2017).

4.2 MARCO-UK model

The UK MAcroeconometric Resource COnsumption (MARCO-UK) model is a macroeconomic representation of the UK economy with a particular emphasis on the demand for energy and its interactions with wider economic developments. The main objective of the MARCO-UK model is to provide a better understanding of the macroeconomic effects in the UK derived from policy changes aimed at reducing energy use and emissions. It has recently been applied to explore the role of increases in thermodynamic energy efficiency as a driver of economic growth in the UK (Sakai et al. 2019). MARCO-UK is a demand-driven model, following the tradition of other similar post-Keynesian-related models, such as E3ME (Cambridge Econometrics 2014), developed by Cambridge Econometrics, and the

[10] Emonts-Holley et al. (2014) give a detailed description of the methods employed to construct these data. The SAM is available for download at: https://doi.org/10.15129/bf6809d0-4849-4fd7-a283-916b5e765950
[11] See Ross et al., (2018a) for the full list of sectors in the aggregate 30 sector 2010 UK SAM.

macroeconomic model used by the Office for Budget Responsibility (OBR 2013). The model is useful to conduct ex-post and ex-ante simulations.

The MARCO-UK model is based on a system of simultaneous equations that represent the relationship between aggregate macroeconomic variables and allows the model to project their interdependent values through time, given the inputs of a limited number of exogenous variables. Generally, the MARCO-UK model contains two types of equations, identities and econometric equations. Identities represent definitions of given variables and must be true in all time periods. They are often derived from accounting relationships. Econometric equations describe relationships that are not defined by accounting rules, but instead depend on the structure of the economy. In simple terms, econometric equations contain parameters that are estimated using rigorous statistical approaches. The econometric equations in the MARCO-UK model are estimated from historical time series of the variables involved. The econometric equations often consist of a long-term and a short-term specification. While the long-term specification describes the long-term trends in the relationship between the variables, the short-term specification describes any short-term deviations from the long-term trends.

The structure and equations of the MARCO-UK model are provided below. More information on the value of the parameters that were statistically estimated can be found in Appendix C, while the data sources used in the MARCO-UK model are described in Appendix D. Appendix E contains an alphabetical list of all variables in MARCO-UK model.

4.2.1 GDP and aggregate demand

At the core of the MARCO-UK model sits the macroeconomic identity through which aggregate GDP (Y) is derived as the sum of the components of aggregate demand.

$$\mathrm{Y_t = C\_T_t + I_t + G_t + X_t - M_t + STAT1_t} \tag{10}$$

Where $\mathrm{C\_T}$ is aggregate consumption by households, I is aggregate investment, G is government expenditure, X is exports, M is imports and $\mathrm{Stat1}$ is a statistical difference (as reported by the ONS). In forward projections all statistical differences are assumed to be zero.

In addition, GDP (Y) is also defined as the sum of gross value added (GVA), net taxes ($\mathrm{NET\_TAX}$) and a statistical difference ($\mathrm{STAT3}$). This equation is solved for GVA, since Y is already defined as an endogenous variable.

$$\mathrm{GVA_t = Y_t - NET\_TAX_t - STAT3_t} \tag{11}$$

Aggregate consumption ($\mathrm{C\_T}$) is composed of two components, namely consumption of energy goods ($\mathrm{C\_E}$) and consumption of non-energy goods ($\mathrm{C\_NE}$).

$$\mathrm{C\_T_t = CNE_t + CE_t} \tag{12}$$

Consumption of non-energy goods ($\mathrm{C\_NE}$) is a function of disposable income (YD), wage income (W) and total useful exergy ($\mathrm{UEX\_TOT}$). This function represents the long-term specification. The short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$CNE_t = f(YD_t, W_t, UEX\_TOT_t) \tag{13}$$

Consumption of energy goods (C_E) is given by the physical amount of final energy used by households (FEN_C) multiplied by its price (P_EN_C).

$$CE_t = ((P\_EN\_C_t) / (CPI_t / 100)) * FEN\_C_t \tag{14}$$

Investment (I) by private firms is expressed as a function of profits made by firms (YF), capital productivity (Y/K_NET), the productivity of useful exergy (Y/UEX_TOT), and labour productivity (Y/L). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$I_t=f(YF_t, Y_t/K\_NET_t, Y_t/UEX\_TOT_t, Y_t/L_t) \tag{15}$$

Exports (X) are a function of GDP from the rest of the world (Y_RW), the price of exports (PX) and total useful exergy (UEX_TOT). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$X_t = f(Y\_RW_t, PX_t, UEX\_TOT_t) \tag{16}$$

Imports (M) are a function of total consumption expenditure (C_T), GDP from the rest of the world (Y_RW), and the real exchange rate (E_INDEX_REAL). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$M_t = f(C\_T_t, Y\_RW_t, E\_INDEX\_REAL_t) \tag{17}$$

The trade balance (TB) is simply defined as exports (X) minus imports (M).

$$TB_t = X_t - M_t \tag{18}$$

Government expenditure (G) is assumed to be exogenous in the model. For forward projections the values of G are set exogenously to grow at the rate of GDP in the OBR's central growth projection.

4.2.2 Income of capital, labour and government

The incomes of labour and capital are key drivers of GDP through their influence on the aggregate demand components C_T and I.

Profits (YF) are determined from GDP (Y) and wage income (W) according to a macroeconomic identity, which expresses Y as a sum of different flows of income and is solved for profits.

$$YF_t = Y_t - W_t - YG_t - STAT2_t \tag{19}$$

Where YG represents government income and $STAT2$ presents a statistical difference as reported by the ONS.

Total wage income (W) is a function of profits received by firms (YF), average hourly wages (W_HOUR), the consumer price index (CPI) and quality adjusted labour (HL). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$W_t = f(YF_t, W\_HOUR_t, CPI_t, HL_t) \tag{20}$$

Average hourly wages (W_HOUR), in turn, is a function of its own level in the previous period (*t-1*), the consumer price index (CPI), labour productivity (Y/L) and the unemployment rate (UR). Importantly, hourly wages are assumed to be sticky and adjust only gradually to changes in the unemployment rate and other variables. This is achieved by including lagged values of W_HOUR in its own specification.

$$W\_HOUR_t = f(W\_HOUR_{t-1}, CPI_t, Y_t/L_t, UR_t) \tag{21}$$

Disposable income (YD) is a function of wage income (W) and net wealth (NW). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$YD_t = f(W_t, NW_t) \tag{22}$$

Net wealth (NW) is a function of its value in time *t-1*, profits made by firms (YF), the unemployment rate (UR) and disposable income (YD).

$$NW_t = f(NW_{t-1}, UR_t, YD_t) \tag{23}$$

Savings, on the other hand, is defined as a ratio, S_RATIO, given as the percentage of disposable income (YD) that is not destined to total consumption expenditure (C_T).

$$S\_RATIO_t = ((YD_t - C\_T_t) \,/\, YD_t) * 100 \tag{24}$$

Government income (YG) is set exogenously to its historical values in the fitting period of the model, 1971-2013. In forward projections values for YG are set to grow in line with Y in the model, so that the ratio YG/Y ($YG\_FRACTION$) is held constant at the value of 2013.

$$YG_t = Y_t * YG\_FRACTION \tag{25}$$

The government budget follows from the difference between government income and government expenditure (YG-G).

4.2.3 Production inputs: labour, capital and useful exergy

In the MARCO-UK model it is assumed that the production of aggregate GDP requires three inputs, namely labour, capital and useful exergy.

Gross capital stock (K_GRS) is defined as the existing stock in time t-1 plus the flow of gross fixed capital formation (I) in period t, minus the amount of obsolete capital that is retired from use (i.e. assets at end of life and loss from scrappage) (K_RETIRE).

$$K\_GRS_t = K\_GRS_{t-1} + I_t - K\_RETIRE_t \quad (26)$$

Net capital stock (K_NET), in turn, is the gross capital stock (K_GRS) minus the depreciation of fixed (DEP_FIX) and non-fixed assets (DEP_NFIX).

$$K\_NET_t = K\_GRS_t - DEP\_FIX_t - DEP\_NFIX_t \quad (27)$$

Capital services (K_SERV) is calculated by multiplying the net stock (K_NET) by an index (K_serv_index).

$$K\_SERV_t = K\_NET_t * K\_serv\_index_t \quad (28)$$

Depreciation of fixed assets (DEP_FIX) is equal to the depreciation rate multiplied by the net capital stock.

$$DEP\_FIX_t = DEP\_RATE_t * K\_NET_t \quad (29)$$

The amount of useful exergy (UEX_TOT) required for production in each year is estimated using an econometric equation and is a function of its own lagged value, Y and the other production inputs HL and K_GRS.

$$UEX\_TOT_t = f(UEX\_TOT_{t-1}, HL_{t-1}, K\_GRS_{t-1}, Y_{t},) \quad (30)$$

Capital and energy services are treated in the model as complements. This means that capital goods cannot be put into work without useful work. This mirrors findings by Santos et al. (2016).

The MARCO-UK model assumes that the requirements of labour inputs (L) (i.e. the employed labour) for any given Y can be described using a Cobb-Douglas production function combining the three factor inputs. It is therefore a function of GDP (Y) and the other two factors of production: capital services (K_SERV) and total useful exergy (UEX_TOT). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$L_t = f(Y_t, K\_SERV_t, UEX\_TOT_t) \quad (31)$$

Quality-corrected labour (HL) is calculated by multiplying labour (L) by two indices: the average annual hours worked by persons engaged (L_HRS_INDEX) and the human capital index, based on years of schooling and returns to education (L_HC_INDEX).

$$HL_t = L_t * L\_HRS\_INDEX_t * L\_HC\_INDEX_t \quad (32)$$

Labour productivity (YL) is simply the ratio between GDP (Y) and labour (L).

$$YL_t = Y_t / L_t \quad (33)$$

The labour force (LF) is defined as the amount of people in the UK economy that are available to work. It is a function of the labour force in time t-1, GDP (Y) and population (POP).

$$LF_t = f(LF_{t-1}, Y_t, POP_t) \tag{34}$$

The unemployment rate (UR) is the percentage of people that are out of work, according to the following equation:

$$UR_t = ((LF_t - Lt) / LF_t) * 100 \tag{35}$$

4.2.4 Sectoral structure

While the key dynamics of GDP, employment and investment are determined at the aggregate level, the MARCO-UK model also disaggregates GDP into two sectors, an industrial (IND_T) and a non-industrial sector (OTH_T). In the model, it is assumed that all the income is spent. In this sense, from the expenditure side, it can be said that GDP (Y) is equal to total expenditure by industry (IND_T) and total expenditure by other sectors (i.e. agriculture and services) (OTH_T).

Total expenditure by industry (IND_T) is the sum of industry expenditure on non-energy (IND_NE) goods and energy (IND_E).

$$IND\_T_t = IND\_NE_t + IND\_E_t \tag{36}$$

Industry non-energy spend (IND_NE) is a function of investment (I), total useful exergy (UEX_TOT) and the real interest rate (R_REAL). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$IND\_NE_t = f(I_t, UEX\_TOT_t, R\_REAL_t) \tag{37}$$

Industry energy spend (IND_E), in turn, is calculated by the physical amount of final energy used by industry (FEN_IND) multiplied by its price (P_EN_IND).

$$IND\_E_t = ((P\_EN\_IND_t) / CPI_t) * FEN\_IND_t \tag{38}$$

Total expenditure by other sectors (OTH_T) can be derived from total expenditure by industry and Y.

$$OTH\_T_t = Y_t - IND\_T_t - STAT1_t \tag{39}$$

Energy spend in other sectors (OTH_E) is similarly calculated to the industry sectors by the physical amount of final energy used by other sectors (FEN_OTH) multiplied by its price (P_EN_OTH).

$$OTH\_E_t = ((P\_EN\_OTH_t) / CPI_t) * FEN\_OTH_t \tag{40}$$

Expenditure on non-energy by other sectors (OTH_NE) is the difference between the total (OTH_T) and their expenditure on energy (OTH_E).

$$OTH\_NE_t = OTH\_T_t - OTH\_E_t \tag{41}$$

4.2.5 Energy use, energy efficiency and CO_2 emissions

One of the characteristics of the model is its incorporation of energy as an indispensable element in the economic system. Hence the availability of energy and changes in the thermodynamic efficiency along the energy conversion chain (i.e. primary, final and useful energy) are an important factor in shaping the economic trajectory of the UK economy in MARCO-UK.

The relevant equations in MARCO-UK are outlined below and a detailed discussion of how the energy and economic system influence each other in the MARCO-UK model can be found in Sakai et al. (2019).

Total final energy (FEN_T) is given by the sum of final energy used by households (FEN_C), industry (FEN_IND) and remaining sectors (i.e. agriculture and services) (FEN_OTH).

$$FEN\_T_t = FEN\_C_t + FEN\_IND_t + FEN\_OTH_t \tag{42}$$

Final energy used by households (FEN_C) is a function of energy prices faced by households (P_EN_C), total useful exergy (UEX_TOT), heating degree days (HDD) and average hourly wages (W_HOUR). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$FEN\_C_t = f(P\_EN\_C_t, UEX\_TOT_t, HDD_t, W\_HOUR_t) \tag{43}$$

Final energy used by industry (FEN_IND) is a function of prices faced by industry (P_EN_IND), total useful exergy (UEX_TOT) and the level of imports (M). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$FEN\_IND_t = f(P\_EN\_IND_t, UEX\_TOT_t, M_t) \tag{44}$$

Final energy used by other sectors (FEN_OTH) is a function of its own level in time *t-1*, prices faced by other sectors (P_EN_OTH) and total useful exergy (UEX_TOT).

$$FEN\_OTH_t = f(FEN\_OTH_{t-1}, P\_EN\_OTH_t, UEX\_TOT_t) \tag{45}$$

Primary exergy (PEX) is calculated by dividing total final energy (FEN_T) by the efficiency to transform primary energy into final energy ($EXEFF\_PF$).

$$PEX_t = FEN\_T_t \,/\, EXEFF\_PF_t \tag{46}$$

Primary energy (PEN), in turn, is calculated by dividing primary exergy (PEX) by the ratio between primary exergy and primary energy (PEX_PEN_RATIO).

$$PEN_t = PEX_t \,/\, PEX\_PEN\_RATIO_t \tag{47}$$

Total energy efficiency (EN_EFF_TOT) is expressed as the combined efficiency of transforming primary energy to final ($EXEFF\_PF$) and the efficiency to transform final energy to its useful state ($EXEFF\_FU$).

$$EN\_EFF\_TOT_t = EXEFF\_PF_t * EXEFF\_FU_t \tag{48}$$

The efficiency to transform final energy to useful exergy ($EXEFF\_FU$) is simply a ratio between total useful exergy (UEX_TOT) and total final energy (FEN_T).

$$EXEFF\_FU_t = UEX\_TOT_t / FEN\_T_t \tag{49}$$

The energy intensity of GDP (EY), which is often used as a proxy for energy efficiency, is calculated as the ratio between total final energy (FEN_T) and GDP (Y).

$$EY_t = FEN\_T_t / Y_t \tag{50}$$

The energy-GDP ratio (EN_GDP_RATIO) represents the share of energy expenditure in GDP. It is calculated by dividing total final expenditure (i.e. the sum of energy expenditure by households, industry and other sectors) by GDP (Y).

$$EN\_GDP\_RATIO_t = (CE_t + IND\_E_t + OTH\_E_t) / Y_t \tag{51}$$

CO_2 per capita ($CO2\_TERR/POP$), from the territorial perspective, is expressed in the reduced form of the Kaya identity, being a function of GDP per capita (Y/POP) and (primary) energy intensity (PEN/Y). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$CO2\_TERR_t/POP_t = f(Y_t/POP_t, PEN_t/Y_t) \tag{52}$$

From a consumption approach, CO_2 per capita ($CO2\_CONS/POP$) is a function of its own level in the previous period (*t-1*), GDP per capita (Y/POP), (primary) energy intensity (PEN/Y) and imports per capita (M/POP). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$CO2\_CONS_t/POP_t = f(CO2\_CONS_{t-1}/POP_{t-1}), Y_t/POP_t, PEN_t/Y_t, M_t/POP_t) \tag{53}$$

4.2.6 Prices and money

As the MARCO-UK model is not based on optimisation, prices play a much less important role in the model than they do in general equilibrium models, where they are key to balancing supply and demand in markets. In general the MARCO-UK model is a representation of the real economy, so all quantities in the model are expressed in real terms. Nevertheless prices play some role in the model.

The general level of prices is represented by the consumer price index (CPI), which is a function of general price of energy (CPI_E), the price of imports (PM), wage productivity (W/Y) and the real exchange rate (E_INDEX_REAL). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$CPI_t = f(CPI\_E_t, PM_t, W_t/Y_t, E\_INDEX\_REAL_t) \quad (54)$$

The general price of energy (CPI_E) is a function of its own levels in the previous period (*t-1*), and the energy prices for households (P_EN_C), industry (P_EN_IND) and others (P_EN_OTH).

$$CPI\_E_t = f(CPI\_E_{t-1}, P\_EN\_C_t, P\_EN\_IND_t, P\_EN\_OTH_t) \quad (55)$$

The relative price of energy (CPI_REL_EN) is thus calculated as the ratio between the general price of energy (CPI_E) and the consumer price index (CPI).

$$CPI\_REL\_EN_t = CPI\_E_t \,/\, CPI_t \quad (56)$$

Energy prices for households (P_EN_C) is expressed as a demand function, given by the amount of final energy consumed by households (FEN_C) and the consumer price index (CPI). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$P\_EN\_C_t = f(P\_EN\_C_{t-1}, FEN\_C_t, CPI_t) \quad (57)$$

Similarly, energy prices for industry (P_EN_IND) is a function of the amount of final energy consumed by industry (FEN_IND) and the consumer price index (CPI). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$P\_EN\_IND_t = f(FEN\_IND_t, CPI_t) \quad (58)$$

Finally, energy prices for other sectors (P_EN_OTH) is a function of the amount of final energy consumed by households (FEN_C) and the consumer price index (CPI). A short-term specification is used with variables expressed in differenced logs, incorporating lags of the endogenous and exogenous variables and an error correction term.

$$P\_EN\_OTH_t = f(FEN\_OTH_t, CPI_t) \quad (59)$$

As outlined below, energy prices also have some influence on the energy consumption in different sectors. Because energy prices in the different sectors are determined through a demand function solved for prices, energy prices are inversely related to the final energy consumption in the relevant sectors. This specification is useful for exploring the effect of price changes on the economy. However, this specification of energy prices is less suitable for exploring scenarios that lead to changes in energy consumption independent of prices and therefore present a limitation in the current study. As energy demand increases, energy prices decrease due to the inverse econometric relationship. However, the econometric equations indicate that energy prices only have a limited influence on the development of the real variables in the model (GDP, employment, investment, consumption). Therefore the effect of this limitation on the results of this study is very small.[12]

The price of exports (PX) is given by its own level in the previous period (*t-1*), the energy price index (CPI_E), GDP of the rest of the world (Y_RW) and the nominal exchange rate (E_INDEX_NOM).

$$PX_t = f(PX_{t-1}, CPI\_E_t, Y\_RW_t, E\_INDEX\_NOM_t) \quad (60)$$

The price of imports (PM) is a function of its own level in the previous period (*t-1*), GDP (Y) of the rest of the world (Y_RW), and the real exchange rate (E_INDEX_REAL).

$$PM_t = f(PM_{t-1}, Y\_RW_t, E\_INDEX\_REAL_t) \quad (61)$$

Inflation (INF) is simply the change of the consumer price index from period *t-1* to period *t*.

$$INF_t = (((CPI_t / CPI_{t-1}) - 1) * 100) \quad (62)$$

Money supply (MS) is a function of its own level in time *t-1*, GDP (Y), the real interest rate (R_REAL), inflation (INF) and the savings ratio (S_RATIO).

$$MS_t = f(MS_{t-1}, Y_t, R\_REAL_t, INcF_t, S\_RATIO_t) \quad (63)$$

The nominal interest rate (R_NOM) is a function of its own level in the previous period (*t-1*), money supply, GDP (Y) and the consumer price index (CPI).

$$R\_NOM_t = f(R\_NOM_{t-1}, MS_t, Y_t, CPI_t) \quad (64)$$

The real interest rate (R_REAL) is calculated by subtracting inflationary effects from the nominal interest rate (R_NOM).

$$R\_REAL_t = R\_NOM_t - INF_t \quad (65)$$

The nominal exchange rate (E_INDEX_NOM) is a function of its own level in the previous period (*t-1*), the relative price of imports (CPI/PM), the ratio between domestic GDP (Y) and GDP from the rest of the world (Y_RW) and the nominal interest rate (R_NOM).

$$E\_INDEX\_NOMt = f(E\_INDEX\_NOM_{t-1}, CPI_t/PM_t, Y_t/Y\_RW_t, R\_NOM_t) \quad (66)$$

The real exchange rate (E_INDEX_REAL) is calculated by multiplying the nominal exchange rate (E_INDEX_NOM) by the relative price of imports (CPI/PM).

$$E\_INDEX\_REAL_t = E\_INDEX\_NOM_t * (CPI_t / PM_t) \quad (67)$$

[12] A sensitivity analysis conducted with energy prices fixed at the baseline level produces only marginal changes to the impact of the exports stimulus on the real economy (e.g. GDP increase of 2.58% rather than 2.61%; final energy consumption increase of 3.30% rather than 3.50 %). More detailed results of this sensitivity analysis are provided in Appendix B.

4.2.7 Data sources and model parameterisation

The econometric equations of the MARCO-UK model are estimated from time-series data. The model is based on annual time series data for 75 variables covering the period 1971-2013. Economic variables are expressed in constant (real) terms based on 2011 UK prices. Data was collected from internationally reputable data sources, including the UK Office for National Statistics, World Bank, Penn World Tables, and the United Nations (see Appendix D). All the parameters in the model equations are therefore grounded in empirical evidence and the wealth of data underlying the MARCO-UK model is a key strength of the model.

The parameters contained in the stochastic econometric equations are estimated using Ordinary Least Squares (OLS) techniques, with variables expressed in logarithms, generally following the procedures suggested by Brillet (2016). Stationarity and cointegration tests are applied to determine the existence of common long-term equilibrium relationships between variables. When cointegrating relationships are identified, econometric equations are estimated using long-run and short-run specifications. The latter involve variables expressed in log differences, and include time lags and an error correction term. All the estimated variables are examined in terms of their goodness of fit (i.e. adjusted R^2). Coefficients are checked for statistical significance and their direction (signs) should not contradict theoretical expectations. Moreover, residuals are tested for normality, heteroscedasticity and autocorrelation.

Once all the stochastic econometric equations have been estimated, they form a system of linear equations together with the identities. It is important to highlight that the model solution does not entail the optimisation of any particular variable. In other words, no optimal behaviour is implied. The system is dynamically solved for each time period using the established Gauss-Seidel iterative method (Varga 2000). This technique allows determination of the values of the endogenous variables, based on the known values of the exogenous variables. The method also requires the actual values of the endogenous variables to be provided for the starting time periods (1971 to 1975 due to the use of time lags), and subsequently uses their estimated values to solve the system for the remaining time periods.

In order to replicate the historical behaviour of all the endogenous variables, dummies were included in order to capture break points in the variables' trends. These dummy variables were applied once a structural break test had been applied, and were mostly used to account for the recessions in mid 1970s, early 1980s, and the financial crisis of 2009.[13] Once the model has been solved, the solution represents the basefit. The basefit model estimation, fitting and results are given in more detail in Appendix C.

The model validation process involved several steps. First, the annual datasets for variables were sourced, and validated. Second, using the annual datasets, the individual equations were assembled to form the basic model architecture, using mainly standard and post-Keynesian economic theory. Third, the basic model results and statistical test results were reviewed, with amendments made to correct any diagnostic errors. Fourth, the improved model was then peer reviewed, and several further refinements were made from the feedback received. A final stage then occurred to review the models results, and making

[13] The MARCO-UK does not include the potential for points in projections of the model into the future, as it is considered that such break points are difficult to anticipate and model in advance.

required improvements to improve fitting to meet statistical tests. The end product was the basefit model covering the period 1971-2013.

5 Simulation results

5.1 UK-ENVI simulation results

We provide a brief summary of the analysis presented in a previous UKERC working paper: Ross et al. (2018a) where the UK-ENVI model is used to identify 'the economic impacts of UK trade-enhancing industrial policies and their spillover effects on key elements of the energy system' by simulating a 5% increase in international exports. We focus here on the underlying adjustment mechanisms and key results that will allow for a detailed comparison with the MARCO-UK model. We do so by outlining aggregate results relevant to policy makers, we then discuss selected impacts on energy policy goals, individual sectors, households, and last we illustrate that the UK-ENVI model can track all of these variables over time. As noted previously, we highlight throughout that alternative visions of the UK economy are significant.

The economy is taken to be in long-run equilibrium prior to the increase in labour productivity, so that when the model is run forward in the absence of any disturbance it simply replicates the base year dataset (the 2010 SAM) in each period. The results presented here are typically percentage changes in the endogenous variables relative to this unchanging equilibrium (unless otherwise specified). All of the effects reported are therefore directly attributable to the exogenous shocks to exports. Given that the CGE model uses annual data, we take each period in the adjustment process to be one year.

To observe the adjustment of all the economic variables through time, simulations are run for 50 periods (years). Results for a range of economic and energy use are reported. While we report selected period-by-period results, the focus is primarily on two conceptual time periods. The first is the short run, which is the period immediately after the introduction of the exogenous shock. Capital stocks are fixed in the short run at industry level but labour is perfectly flexible across sectors. In the long run, capital stocks fully adjust, across all sectors, to the shock, and are again equal to their desired levels. However, we also report period-by-period values for a sample of key variables.

We start by discussing the aggregate long-run results for the FNW-FRW closures since this is a useful benchmark, whose properties are well-known. We then discuss the main differences between the FNW-FRW, BRW (our default model), and ELS closures (see Section 4.1.3 for details of the labour market in the UK-ENVI model). This is followed by a brief discussion of the potential impacts on the energy-systems, sectoral results, and a discussion of short-run results.

The short- and long-run macroeconomic simulation results for a 5% increase in international exports, reported in percentage changes from base year, across the different labour market closures, are summarised in Table 1.

5.1.1 Long-run results

The adjustments seen in the long-run for the FRW-FNW closures are akin to the results found in Input-Output modelling. With no supply restrictions applying, prices remain unchanged in the long run (McGregor et al., 1996)[14]. The long-run results for the FRW and the FNW closures are the same as they both tie down wages in the long-run with no changes in prices.

As there are no changes in prices (CPI remains unchanged from base), there is no crowding out of exports in the long run so that exports increase by the full 5%. The increase in exports stimulates aggregate demand, which increases consumption, investment, and GDP, by 1.4%, 2.3% and 2% respectively. Capital stocks rise in the long run by 2.3%, with net investment driven by the (positive) gap between the capital rental rate and the user cost of capital that opens in the short run.

The stimulus to investment and enhanced capacity reinforces the expansion (and the impact on employment). This expansion stimulates the demand for labour so that employment rises by 1.9%, and the unemployment rate falls by 1.8%. Labour income and capital income both rise, by 1.9% and 2.35%, respectively. Export industries tend to be more capital intensive than the aggregate economy, so that the demand for capital increases slightly more than that for labour.

The public sector deficit falls by 7% in the long run, a fall from £98bn to £91bn, as tax revenues rise in response to the stimulus to economic activity. Although not dealt with here, the consequences of closing the Government budget constraint is explored in Ross et al. (2018a).

Imports increase by 2.1% along with increases in domestic demand. In the base period net exports are negative i.e. the UK economy imports more than it exports. The stimulus to exports thereby decreases the negative trade balance by 0.1%.

When considering the BRW case, the stimulus to the real economy is significantly less (as compared to FRW/FNW) because real wages and prices rise in response to the excess demand for labour. Therefore, GDP in the BRW case increases by 0.9%, which is less than half of the 2% stimulus under FRW/FNW. The rise in the real and nominal wage pushes up the CPI (by 0.7%), reducing competitiveness and crowding out some of the stimulus to exports, which now rise by only 3.6% in the long run. The rise in consumption of 1.1% is less than under FRW (1.4%), but the decline is mitigated by the fact labour income actually rises more in this case, with the higher real wage more than offsetting the lower employment impact (0.7% as against 1.9%).

[14] Input-Output is a general equilibrium system with fixed coefficient technologies, an absence of capacity constraints and an infinitely elastic supply of labour. McGregor et al. (1996) demonstrate that regional CGEs generate Input-Output results in long-run equilibria given these assumptions.

Table 1: Short and long-run effects of a 5% increase in international exports in UK-ENVI. % changes from base year.

	Long-run			Short-run			
	FRW-FNW	BRW	ELS	FNW	FRW	BRW	ELS
GDP	2.08	0.95	0.23	0.64	0.30	0.19	-
CPI	-	0.75	1.24	0.92	1.09	1.24	1.40
Unemployment rate (pp difference)	-1.80	-0.71	-	-0.98	-0.46	-0.29	-
Total employment	1.91	0.75	-	1.04	0.49	0.31	-
Nominal gross wage	-	1.61	2.68	-	1.09	1.58	2.28
Real gross wage	-	0.86	1.43	-0.91	-	0.34	0.87
Households wealth	1.36	1.06	0.87	0.43	0.50	0.55	0.61
Households consumption	1.46	1.16	0.96	0.70	0.56	0.75	0.83
Labour income	1.91	2.38	2.69	1.04	1.58	1.90	2.28
Capital income	2.35	1.99	1.76	3.84	2.97	2.83	2.43
Government budget	-7.03	-2.42	0.59	-1.00	0.22	0.76	1.55
Investment	2.35	1.28	0.59	3.35	2.46	2.01	1.36
Total energy use (intermediate+final)	2.53	1.72	1.21	1.30	1.04	1.03	0.93
- Electricity	2.03	1.26	0.77	1.16	0.83	0.81	0.68
- Gas	1.98	1.35	0.94	0.81	0.63	0.70	0.68
Energy use in production (total intermediate)	2.36	1.41	0.80	0.79	0.55	0.52	0.42
Energy consumption (total final demand)	2.91	2.44	2.15	1.56	1.49	1.59	1.64
- Households	1.43	1.30	1.21	0.75	0.68	0.92	1.05
- Investment	2.27	1.26	0.60	2.24	1.55	1.40	1.05
- Exports	5.00	4.11	3.53	2.66	2.63	2.55	2.49
Energy output prices	-	0.50	0.82	0.92	0.98	1.06	1.13
Energy intensity (Total energy use/GDP)	0.44	0.76	0.98	0.66	0.74	0.84	-
Territorial CO2 emissions	2.77	1.69	1.00	0.66	0.46	0.43	0.35
Emission intensity (territorial CO2/GDP)	0.67	0.73	0.77	0.02	0.16	0.24	-
Total imports	2.12	2.77	3.19	3.07	3.06	3.28	3.41
Total exports	5.00	3.63	2.75	3.00	2.73	2.49	2.25
Net exports (exports-imports)	-0.19	-0.04	0.06	0.04	0.05	0.09	0.12
- Electricity	2.18	2.27	2.33	2.42	2.25	2.41	2.45
- Gas	2.29	2.46	2.58	2.68	2.53	2.70	2.77

Note: Short- and long-run are two conceptual time periods. The short run is the period immediately after the introduction of the exogenous shock. Capital stocks are fixed in the short run at industry level. In the long run, capital stocks fully adjust, across all sectors, to the shock, and are again equal to their desired levels. The short run applies to a period of a year; the adjustment period to the long run varies but is typically complete within 7-12 years. See Ross et al. (2018a) for a full set of results.

Next, we consider the ELS case of continuous full-employment, where we assume an exogenous labour supply curve (and participation rate). As we know, following the demand stimulus the real wage rises to choke off any excess demand for labour at the original level of employment. So employment is unchanged, but the real wage and the CPI rise by 1.4% and 1.2%, significantly more than under the BRW (0.8% and 0.7%). This results in much greater crowding out of exports, which now only rise by 2.75%, and a much bigger stimulus to imports (of 3.1%). The sectoral distribution of effects does result in a modest stimulus to GDP of 0.2%, but this is significantly less than under the BRW and FRW-FNW closures.

5.1.2 Short-run results

The short-run impacts are muted in comparison to these seen in the long run, given that the capital stock is fixed in the short run - both in total and in its distribution across sectors - and prices increase in all cases so that there is some induced loss in competitiveness, with exports always crowded out to a degree. The GDP (and employment) effects in the short run are ranked as: FNW>FRW>BRW>ELS (and indeed the impact is zero in this final case).

5.1.3 Energy results

Focusing on the BRW case, our preferred model, it can be seen that total energy use (intermediate plus final demand) increases significantly, by 1.7%. Electricity use increases by 1.26% and Gas use by 1.3%. This reflects increases in energy use in both production and final demand, notably consumption. Energy use in production (total intermediate) increases by 1.41% in the long run in the BRW case. This is driven by the increase in intermediate demands from exporting sectors (we explore this in more detail when considering sectoral results), and their linkages to the energy sectors.

The use of energy in consumption (total final demand) sees a significant increase of 2.4%. This increase is mainly driven by the stimulus to exports. Although household and investment demands for energy increase by 1.3% and 1.2%, this constitutes a marginal contribution to total final demands in absolute terms.

Energy use increases across the board in response to the export stimulus. Furthermore, energy use increases significantly relative to GDP, employment and investment. Energy intensity, defined here as energy use per unit of GDP, increases. In fact, this is true across all labour market specifications: energy intensity increases significantly as a consequence of the successful export promotion strategy. Similarly, industrial territorial CO_2 emissions and emission intensity increase across all closures.

Industrial territorial CO2 emissions increase here in all cases. This is the incremental change in emissions that is likely to arise from the increase in exports alone. This identifies the additional challenge made to meeting the Government's emission targets that is solely attributable to the increase in exports. Of course, in practice, energy policies directed at decarbonisation are in place, and it is instructive to consider how these might be adjusted to counter any adverse effects on emissions generated by the expansion in exports. An idea of the scale of the change required is to consider by how much the emissions in the electricity producing sector would need to fall so as to offset entirely the emissions directly attributable to the increase in exports. A fall of 8% in emissions in the electricity sector would offset the 2.77% increase in emissions arising in the FRW closure from the 5% increase in exports. Given that emissions in the electricity production sector have fallen by nearly 50% in the UK over the last years it is clearly feasible that these emissions could be offset. This said, other things being equal some adjustment in energy policy at the margin would be required to offset the additional emissions associated with an expansion in exports.

Energy output prices increase by 0.5% reflecting the stimulus to (derived) energy demand created by the expansion, as well the increase in labour and material costs.

5.1.4 Sectoral results

The UK-ENVI model allows us to track impacts across 30 individual sectors of the UK economy (with the basis of 94 industrial sectors given in the IO/SAM). Figure 3 summarises selected long-run results at the individual sector level for the 5% increase in international exports, for the BRW labour market closure. Ross et al. (2018a) give a more detailed set of sectoral results and an analysis of differential impacts across sectors, and the underlying transmission mechanisms.

Although we do not discuss these results in detail here, it is evident that aggregate energy and economy-wide impacts are driven by key characteristics of individual sectors. Although all sectors receive the same exogenous increase in export demands, sectoral impacts vary significantly because of their heterogeneous nature. Sectors differ in terms of, for example, energy intensity, export intensity and domestic demand linkages and these seem to be driving aggregate impacts on energy.

This highlights potential policy trade-offs, particularly at the individual sector level. The ability to identify sector specific impacts is particularly important when policy is targeted at individual sectors. Moreover, the sectoral disaggregation allows the modeller to identify potential trade-offs ('winners and losers') across sectors of the economy.

5.1.5 Household results

Given that real wages (and capital incomes) are rising, Households' experience rising incomes and wealth and so their total consumption - of energy and non-energy goods & services – increases, as we have already noted. The UK-ENVI model allows us to track distributional impacts of policies across individual household groups. Figure 4, for example, summarises the long-run impacts on households' consumption, income, the share of income spent on Electricity & Gas, and non-energy goods & services, across household quintiles, where HH1 is the lowest income quintile. From this, we can identify the impact on e.g. fuel poverty and other distributional effects. The ability to track such changes across households is of significant importance when analysing distributional effects of policies, for example.

5.1.6 Time path adjustments

The time path adjustments for GDP, employment, and total energy use are detailed in Figure 5. This shows how these variables increase throughout all of the simulation periods. Moreover, these results highlight that total energy use increases more than proportionately to GDP, and the increase in energy intensity previously noted.

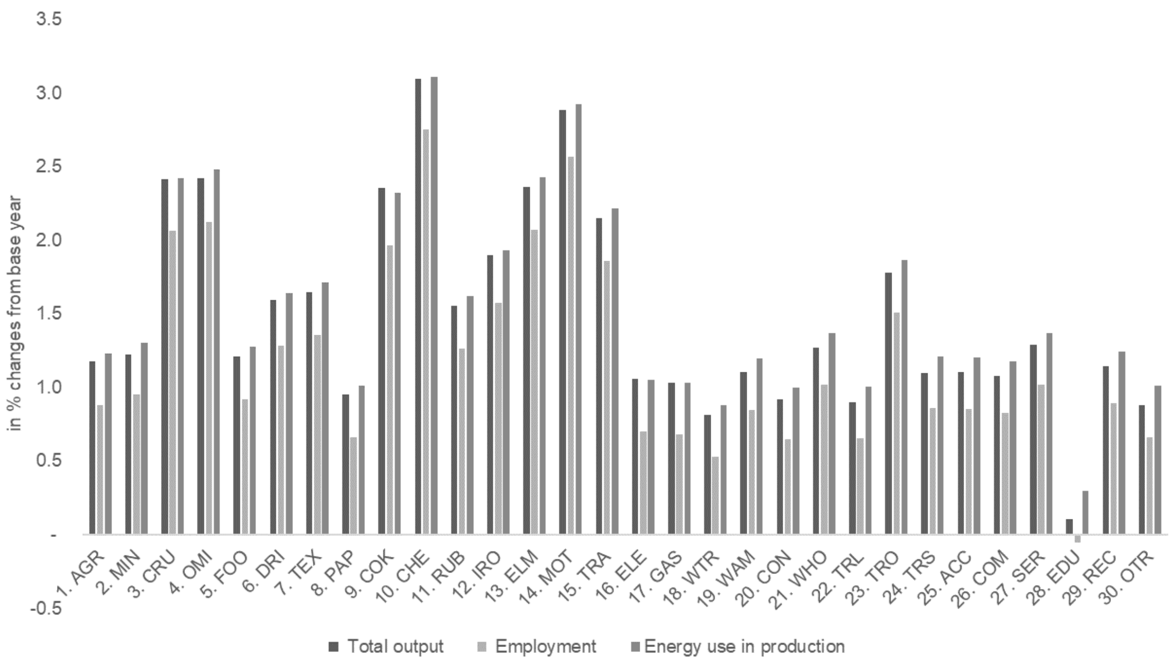

Figure 3: Long-run effects on output, employment, and energy use by individual sectors of a 5% increase in international exports, BRW closure. % changes from base year.

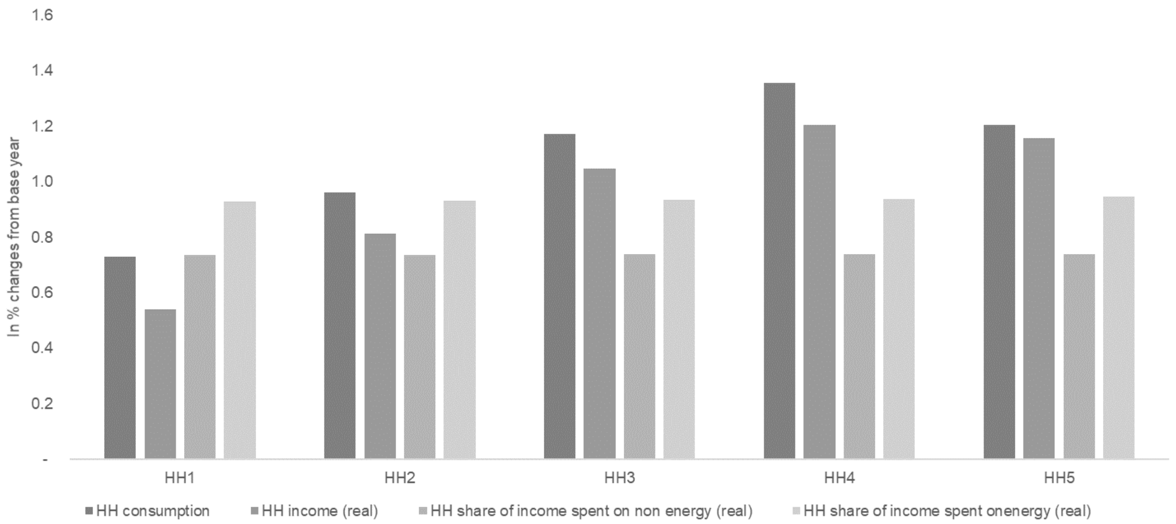

Figure 4: Long-run effects on household quintiles of a 5% increase in international exports, BRW closure. % changes from base year.

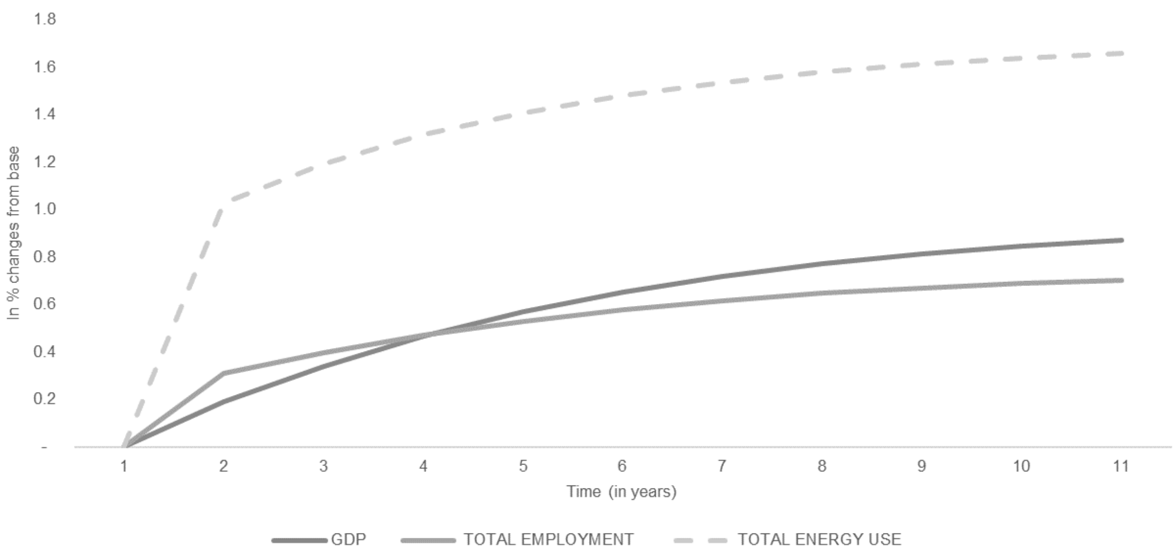

Figure 5: Aggregate transition path for GDP, employment, and total energy use of a 5% increase in international exports. % changes from base year.

5.2 MARCO-UK simulation results

As discussed in section 2.2.2, MARCO-UK does not feature the same conceptual distinction between the short run and the long run as the UK-ENVI model. To compare long-term impacts we use the results of the last year in the MARCO-UK projection, 2050, which are discussed in Section 5.2.1. In response to the increase in exports, the UK economy in MARCO-UK shows a period of transitional, fluctuating dynamics, before it settles to a new and stable growth trajectory (approx. after 2030). These transitional dynamics are discussed in section 5.2.2. To facilitate comparison of short-term impacts with UK-ENVI, we report the average values of the first three years after imposition of the export shock, 2014-2016, to represent the short-term impacts. Section 5.2.3 discusses energy and emission impacts in the export shock scenario.

5.2.1 Long-term impacts

By 2050 the export shock leads to permanent increases in GDP compared to the baseline (2.61%), including all its endogenous components, i.e. consumption (2.10%), investment (1.22%) and net exports (4.52%) (Figure 6, 2). However, while the export shock leads to a permanent increase in GDP it does not affect the growth rate, so that the difference in GDP settles to a constant proportion (Figure 7). The increase in GDP is accompanied by a reduction in the unemployment rate (0.1 percentage points lower), elevated wage income (2.01%) and significantly higher profits (3.51%) (Figure 8). In addition, the export shock leads to a significant shift in the way production factors are used in the economy. After some transitory adjustments, the long-term growth trajectory under the export scenario is characterised by increasing capital and useful exergy intensity (0.44% and 1.27%) but declining labour intensity of production (-2.09%) (Figure 9). The model results indicate that the increase in economic output is larger in the non-industrial sectors (2.81%) than in the industrial sectors (1.04%).

Table 2: Short- and long-term effects of a 5% increase in international exports for some key variables in the MARCO-UK model. Results are presented as % deviation from the baseline scenario, with the exception of the unemployment rate which is presented as percentage point difference in the rate between the export scenario and baseline scenario.

Variable	Symbol	Short-term	Long-term
		Average year 1-3 (2014-2016)	Year 37 (2050)
GDP	Y	3.05	2.61
Consumption	C_T	2.00	2.10
Investment	I	6.33	1.22
Government expenditure (exogenous)	G	0.00	0.00
Total imports	M	2.75	3.11
Total exports	X	5.00	5.00
Total employment	L	1.33	0.47
Unemployment rate (pp difference)	UR	-1.09	-0.10
Profit (Capital income)	YF	4.62	3.51
Wage income	W	1.83	2.01
Hourly wages	W_HOUR	1.29	1.34
Government income	YG	3.05	2.61
Government budget	YG-G	-4.63	-3.25
Capital service intensity	K_SERV/Y	-1.86	0.44
Useful exergy intensity	UEX_TOT/Y	-1.02	1.27
Labour intensity	L/Y	-1.69	-2.09
Final energy intensity	FEN_T/Y	-1.98	0.86
Total final energy consumption	FEN_T	1.03	3.50
Total useful exergy consumption	UEX_TOT	2.02	3.92
Energy use by households	FEN_C	1.76	2.97
Energy use by industry sectors	FEN_IND	1.10	2.09
Energy use by non-industry sectors	FEN_OTH	0.59	4.05
CO_2 emissions (territorial)	CO2_TERR	1.43	2.84
CO_2 emissions (consumption-based)	CO2_CONS	2.14	3.24
Output of industrial sectors	IND_T	1.96	1.04
Output of non-industrial sectors	OTH_T	3.31	2.81
CPI	CPI	0.15	-0.43
General price of energy	CPI_E	-0.37	-4.60

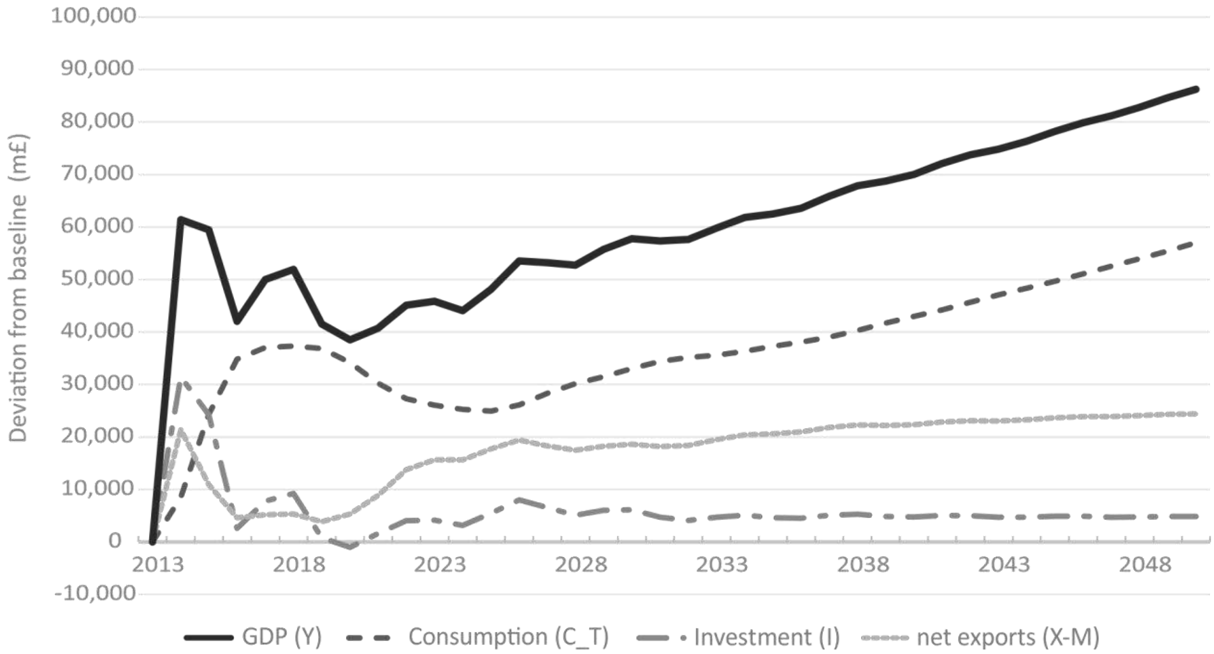

Figure 6: Change in aggregate demand components in MARCO-UK in response to a 5% increase in exports applied from 2014. Absolute deviation from baseline scenario in million £.

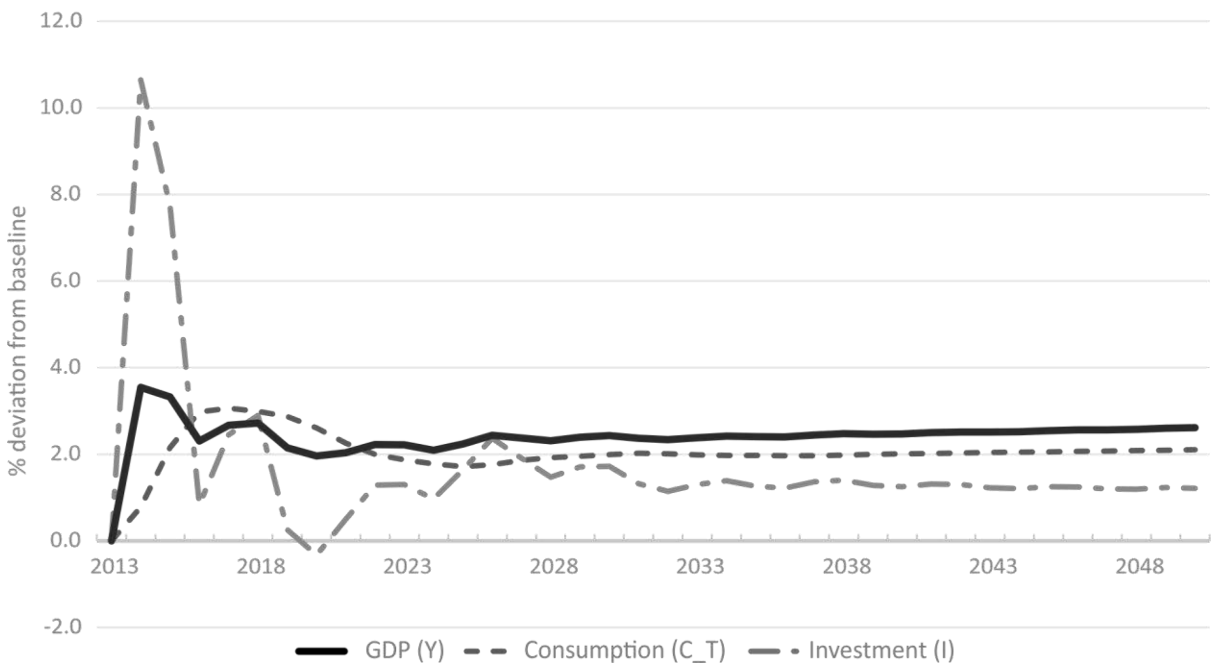

Figure 7: Change in aggregate demand components in MARCO-UK in response to a 5% increase in exports applied from 2014. % deviation from baseline scenario. Net exports are not shown because the baseline values fluctuate close to zero so that % changes are not informative.

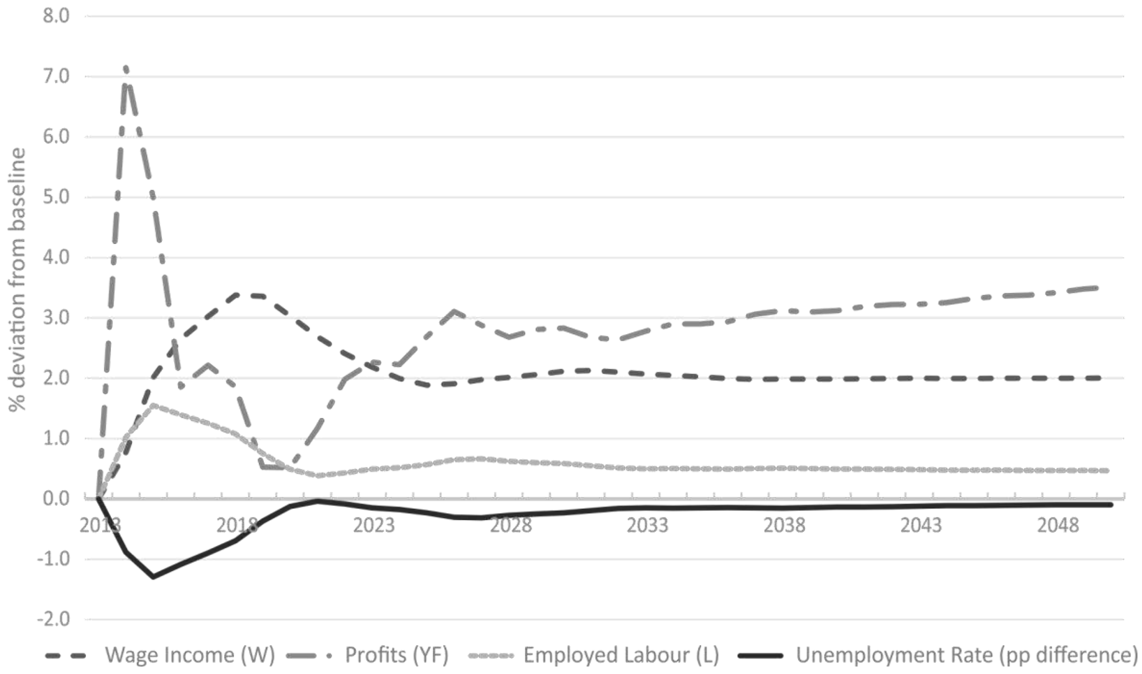

Figure 8: Change in wage income, profits and employment in MARCO-UK in response to a 5% increase in exports applied from 2014. % deviation from baseline scenario.

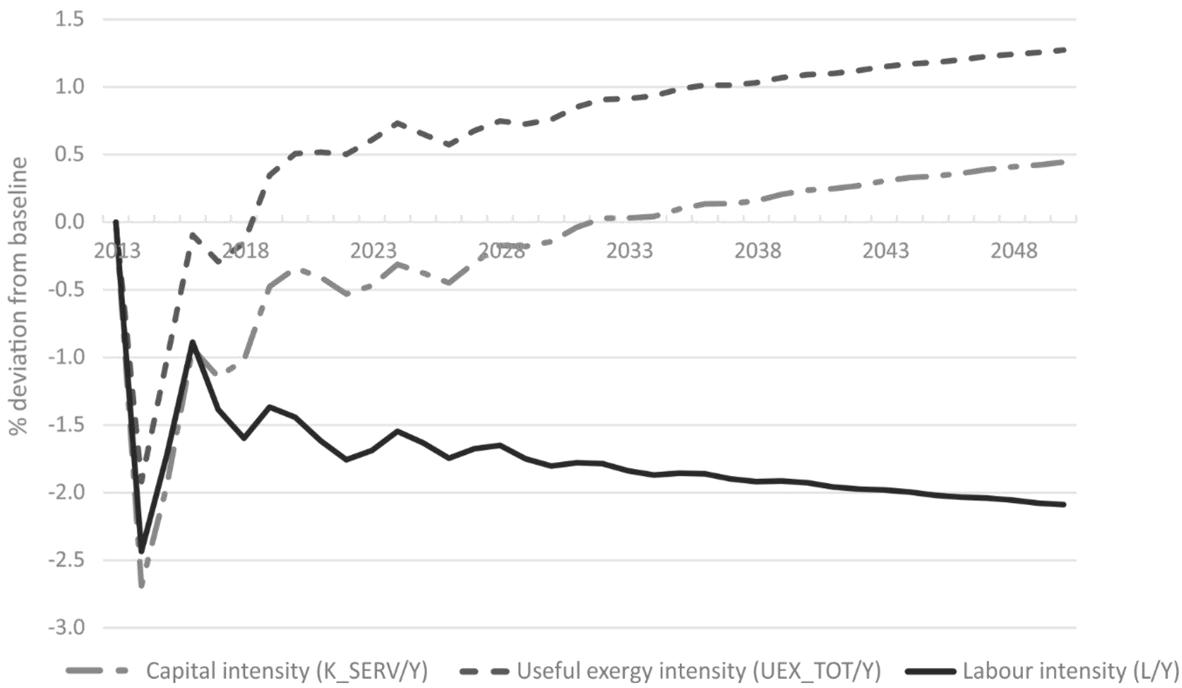

Figure 9: Change in in the intensity of the three production factors in MARCO-UK in response to a 5% increase in exports applied from 2014. % deviation from baseline scenario.

The key drivers through which the export stimulus produces the new growth trajectory are profits and investment. Firstly, the increase in exports leads to higher profits, as GDP increases but wage income does not adjust immediately (see short-term results). Increased levels of profit lead to increased levels of investments and higher capital stocks. The econometric equations also determine that capital stocks increase more than GDP so that the capital intensity of the economy increases. As capital stocks are largely complementary to useful exergy consumption, the useful exergy consumption of the economy also increases.

More importantly, however, the increase in capital stocks directly reduces the need (and hence employment) for labour, because capital is substituted for labour. Therefore, the labour productivity of the economy (aggregate GDP over employed labour in MARCO-UK) increases.

The replacement of labour with capital and the increase in labour productivity is crucial for explaining why the profits and investment remain permanently higher and the model does not revert to the baseline growth path. Without the improvements in labour productivity, unemployment would rise. Rising unemployment would increase hourly wages and wage income which, in turn, would reduce profits. While hourly wages and wage income do rise as a result of the export shock, their rise is not sufficient to cancel out the increases in profit, so that overall the balance between wage income and profit income shifts in favour of profits.

A second important consequence of the relatively smaller increase in wage income is the fact that imports never fully adjust to the increase in exports. Imports in the MARCO-UK model are strongly influenced by aggregate consumption, which is in turn strongly dependent on wage income. As imports do not increase as strongly as exports, net exports are permanently increased and form an important contribution to the long-term increases in GDP.

The overall price level in the economy, as represented by the CPI, is slightly reduced in the long-term (Table 2). This is largely due to a significant reduction in the price of energy, which is driven by increases in energy use as a result of the econometric equations in the model, where higher energy demand is associated with lower prices. This is somewhat counterintuitive and presents a limitation to the model. However, as discussed in section 4.2.6, there is not a strong feedback from prices to the dynamics of the real economy.

5.2.2 Adjustment dynamics

Before the economy settles on the new, long-term growth trajectory it goes through a phase of adjustment showing some cyclical dynamics, which are most easily observed in the investment time series (Figure 7). These cyclical dynamics are result of the abrupt imposition of the export stimulus. An alternative scenario in which the export stimulus is slowly increased to 5% over the whole time period produces similar results in 2050 but with a much smoother adjustment process (see Appendix B). The key factor producing these cyclical dynamics is the somewhat delayed response of wages (and hence consumption and imports) to changes in GDP and unemployment. The dynamics of the adjustment cycle can be described as follows:

Firstly, the exogenous increase in export demand provides a large stimulus to GDP (3.55%) in 2014 immediately after its imposition. This stimulus to GDP is bigger than what would be produced from the export increase alone (a 5% increase in exports in 2014 would lead to a 1.02% increase in GDP, everything else being equal). The strong stimulus to GDP is the result of a number of feedback effects. For example, the increase in exports increase capacity utilisation (approximated in MARCO-UK by the ratio of Y/K) as capital stocks do not fully adjust immediately. Also, the response of wages is also delayed so that profits increase significantly. Both of these effects lead to increased levels of investments which increase GDP even further. As a result of the stimulus to GDP the unemployment rate drops.

Secondly, in the following years (2015-2020), wages, consumption and imports increase in response to the increased GDP and reduced unemployment. Due to the time lags, they not only catch up but also overshoot the new long-term trend (i.e. the new long-term growth trajectory described in section 5.2.1). This reduces profits and investments, as well as net exports. Therefore GDP and employment fall but remain elevated compared to the baseline.

Thirdly, over the period from 2020 to 2025, wages are reduced in response to increased unemployment (again after a certain time lag). Hence, consumption and imports fall below the new long-term trend. With falling wages and consumption, net exports and profits (and investment) rise again. This essentially restarts the cycle, and a second iteration can be observed before the model settles to the new long-term trajectory. However, the second cycle is much less pronounced, because by the time it starts (ca. 2020) previous increases in investment mean that capital stocks and therefore labour productivity have adjusted to the new long-term trend, reducing the impact of changes in GDP on employment and wages.

5.2.3 Energy and emissions results

As described above, a key characteristics of the export scenario are elevated levels of profit, investment and labour productivity. However, these increases come at the cost of an increased intensity of capital and useful exergy in production. In combination with increased GDP, the increased exergy intensity leads to significant increases in the use of useful exergy in the long run (3.92%). A key feature of the MARCO-UK model is an endogenous representation of the efficiency with which final energy can be converted into useful exergy (EXEFF_FU). The increase in investment increases EXEFF_FU compared to the baseline scenario, but this increase is limited as the efficiency is approaching thermodynamic limits. Overall the final energy to useful exergy efficiency only increases by 0.09% in absolute terms. This increase is not sufficient to counterbalance the increased use of useful exergy so that final energy consumption also increases significantly (3.50%).

MARCO-UK determines territorial CO_2 emissions from economic output and its primary energy intensity according to econometrically determined relationships. It does not take into account any potential future policy action that could change the relationship between energy use and CO_2 emissions. As a result the increased energy consumption stimulated by the export shock leads to a 2.84% increase in territorial CO_2 emissions by 2050. This increase is bigger than the increase in GDP (2.61%) which indicates that the carbon intensity of the UK economy deteriorates as a result of the export shock. In addition MARCO-UK projects the global CO_2 associated with final demand in the UK using similar econometric equations. The model projects that these consumption-based CO_2 emissions increase by 3.24% by 2050, even more than territorial CO_2 emissions.

6 UK-ENVI and MARCO-UK simulation results compared

Table 3 summarises key simulation results for the UK-ENVI and MARCO-UK models. We compare the simulation results across the two models systematically by focusing on long- and short-run impacts, the impacts on prices and emissions. Last, we outline possible policy implications. When comparing the results of MARCO-UK and UK-ENVI it needs to be considered that MARCO-UK reports all variables in real terms, while UK-ENVI generally features nominal values, unless specified otherwise. However, as prices in MARCO-UK are only affected very slightly by the export shock (Table 2), we consider that MARCO-UK results remain broadly comparable to UK-ENVI results.

6.1 Long-run effects on GDP and employment

As discussed above, the long-run vision of the economy embedded in the FNW and FRW configurations of UK-ENVI is closest to the post-Keynesian characteristics of MARCO-UK for the long-run response to an export shock. These CGE configurations behave "as if" it was the case that "only-demand-matters", with the supply side of the economy adjusting fully to demand, and no change in wages or prices (McGregor et al., 1996)[15]. The FNW/FRW results act as a benchmark case, which exhibit Input-Output type results in the long-run in response to a demand disturbance.

In the long run, the qualitative nature of the results is similar across models in that the stimulus to exports creates an expansion in the UK economy, reflected in higher GDP and employment in MARCO-UK and in all of the configurations of UK-ENVI (even in the model in which supply is severely constrained by a fixed level of employment, ELS). In this sense, the results are reassuring from the perspective of UK industrial policy, in that the economy is indeed stimulated by the increase in exports. However, total energy use is also typically stimulated as is energy intensity.

However, while there are similarities in terms of qualitative model responses to the export stimulus in the long run there are also significant differences in terms of the scale of the effects. Overall, the impact of the export stimulus on GDP in the MARCO-UK model is bigger than in any of the UK-ENVI configurations. As anticipated, the CGE model that generates results closest to those in MARCO-UK is that with the fixed wage.

As explained above the FNW and FRW models generate identical results in the long run, resulting in a 2.1% stimulus to GDP, in contrast to the 2.6% rise in MARCO-UK. Part of the difference is attributable to a greater stimulus to consumption in MARCO-UK (2.1% compared to 1.4%) despite a similar rise in wealth (1.2% against 1.3%) and wage income (2.0% against 1.9%). The difference in consumption therefore results from the fact that consumption in MARCO-UK generally increases in line with wage income but is more closely aligned with wealth in UK-ENVI.

[15] Input-Output is a general equilibrium system with fixed coefficient technologies, an absence of capacity constraints and an infinitely elastic supply of labour. McGregor et al. (1996) demonstrate that regional CGEs generate Input-Output results in long-run equilibria given these assumptions.

Table 3: UK-ENVI and MARCO-UK simulation results compared. Short and Long-run effects of a 5% increase in international exports. (Results reported as % changes from base year/ baseline scenario.)

	Long-run results				Short-run results				
UK-ENVI/MARCO-UK variables	FRW-FNW	BRW	ELS	MARCO-UK	FNW	FRW	BRW	ELS	MARCO-UK
GDP	2.08	0.95	0.23	2.61	0.64	0.30	0.19	0.00	3.05
CPI	0.00	0.75	1.24	-0.43	0.92	1.09	1.24	1.40	0.15
Unemployment rate (pp difference)*	-1.80	-0.71	0.00	-0.10	-0.98	-0.46	-0.29	0.00	-0.97
Total employment	1.91	0.75	0.00	0.47	1.04	0.49	0.31	0.00	1.33
Real gross wage/ Hourly wage	0.00	0.86	1.43	1.34	-0.91	0.00	0.34	0.87	1.29
Households wealth/ Net wealth	1.36	1.06	0.87	1.22	0.43	0.50	0.55	0.61	2.19
Households consumption	1.46	1.16	0.96	2.10	0.70	0.56	0.75	0.83	2.00
Labour income/ Wage income	1.91	2.38	2.69	2.01	1.04	1.58	1.90	2.28	1.83
Capital income / Profits	2.35	1.99	1.76	3.51	3.84	2.97	2.83	2.43	4.62
Government budget	-7.03	-2.42	0.59	-3.25	-1.00	0.22	0.76	1.55	-4.63
Investment	2.35	1.28	0.59	1.22	3.35	2.46	2.01	1.36	6.33
Total energy use	2.53	1.72	1.21	3.50	1.30	1.04	1.03	0.93	1.03
Energy intensity (Total energy use/GDP)	0.44	0.76	0.98	0.86	0.66	0.74	0.84	0.00	-1.98
Energy output prices/ General price for energy	0.00	0.50	0.82	-4.60	0.92	0.98	1.06	1.13	-0.37
CO_2 emissions (territorial)	2.77	1.69	1.00	2.84	0.66	0.46	0.43	0.35	1.43
Total imports	2.12	2.77	3.19	3.11	3.07	3.06	3.28	3.41	2.75
Total exports	5.00	3.63	2.75	5.00	3.00	2.73	2.49	2.25	5.00

Note: MARCO-UK results are all in real terms, while UK-ENVI results are presented in nominal terms, unless otherwise specified. See Section 5.1 for full set of UK-ENVI results and Section 5.2 for full set of MARCO-UK results.

However, the bigger increase in consumption in MARCO-UK is somewhat offset by a larger increase in imports compared to UK-ENVI FRW-FNW (3.1% against 2.1%) and a smaller increase in investment (1.2% against 2.3%). These effects partially cancel out to produce the overall difference of 0.5% in the increase of GDP. MARCO-UK features lower investment despite significantly higher increases in capital income compared to UK-ENVI FRW-FNW (3.5% as against 2.3%).

One factor that likely contributes to the higher effect on GDP in MARCO-UK is the treatment of government income. In both models, government expenditure is fixed at baseline levels. However, based on a detailed representation of the UK tax system, UK-ENVI FRW-FNW predicts that the export stimulus would increase government revenues and hence reduce the government budget deficit by 7%. In contrast, government income in MARCO-UK simply increases with GDP, indicating a reduction in the government budget deficit by 3.2%. This means that in UK-ENVI FRW-FNW government income soaks up a larger amount of additional income that is not recycled into spending and further economic activity. Given that the representation of taxes in UK-ENVI are much more detailed, this difference effectively reflects an implicit transfer of increased tax revenues to firms (and households) in MARCO-UK. Recycling increased tax revenues into government spending in UK-ENVI's fix-wage models would add to the scale of multiplier effects therein and would close the gap between the models' results. Ross et al., (2018a) report results where the increase in tax revenues in response to the export stimulus is used to finance an increase in current government expenditure. In this case GDP increases by 3.2% in the long run in the FRW closure, and by 1.0% in the BRW case.

Of course, the contrast in results between MARCO-UK and UK-ENVI are even greater in circumstances where the supply-side "matters": that is, where there is some form of binding constraint on the supply side of the economy. This is true of all the short-run variants of UK-ENVI, in which capital stocks are fixed – a case we discuss below – but it is also true of the BRW and ELS variants in the long run. Of course, ELS provides the limiting case in which employment is taken to be fixed to its initial "full-employment" level. Here GDP still increases, but only by 0.2%, which reflects the impact of a sectoral reallocation of resources in favour of exporting sectors: labour demand increases in these sectors, pushing up real wages (ultimately by 1.4%) which reduces labour demand elsewhere. In effect, export-intensive sectors push up wages and prices and "crowd out" other sectors, restoring equilibrium at the original employment level, but with a significantly higher real wage and higher prices. Notice that exports only rise by 2.7% here, given the attendant rise in prices. Export-intensive sectors also tend to be value-added intensive and so GDP increases as a consequence of the sectoral shifts.

The BRW variant of UK-ENVI provides an intermediate case between the effectively infinitely elastic labour supply of the fix-wage cases and the zero elasticity of labour supply in the ELS case. The results reflect this with a stimulus to GDP of 0.9% and to employment of 0.7%.

In terms of GDP, MARCO-UK results are therefore most similar to the UK-ENVI results in the FRW-FNW configurations. However, there are striking differences between MARCO-UK and UK-ENVI FRW-FNW with relation to employment and wages. As discussed above, the labour income in both models is very similar. However, in MARCO-UK this is largely the result of higher real wages (1.3% increase) combined with only a smaller increase in employment (0.4%). In contrast, the real wage in the UK-ENVI FRW-FNW models is fixed in the long run but the export shock leads to a larger increase in employment (1.9% increase). The explanation of the distinctive behaviour of MARCO-UK lies in the endogenous improvements in labour productivity. Higher investment and capital stocks triggered by the export shock in MARCO-UK directly improve labour productivity, which means that employment increases much less than GDP, but wages increase significantly more than in UK-ENVI FRW-FNW (see Table 3). The increase in labour productivity in MARCO-UK is not specific to an export stimulus but would similarly apply for other kinds of demand shocks as it represents a direct relationship between employment and the capital intensity of the economy. In contrast, wages in UK-ENVI only rise in response to a demand stimulus if labour supply is constrained. While wage rises increase consumption, the net effect of labour supply constraints negatively impacts GDP, so that wage rises in the BRW and ELS configurations are accompanied by smaller increases in GDP. However, if a separate empirically robust link between exports and productivity was established, it could be incorporated directly into UK-ENVI; this would facilitate simultaneous increases in both real wages and employment in response to an export stimulus.[16]

6.2 Short-run effects on GDP and employment

The differences in short-run results are marked. Assuming all other things being equal, a 5% increase in exports is equivalent to an approximate 1.5% increase in GDP in 2010 according to data in MARCO-UK. However, in UK-ENVI capital stocks are fixed in the short run and impose a constraint on supply. Hence, the greatest stimulus in the CGE model in the short-run (under FNW) is 0.6% (less than a third of its new long-run value). This stands in contrast with a 3% increase in MARCO-UK (17% above its long-run value). MARCO-UK assumes that there are no supply constraints in the short run due to margins of unused capacity.

As discussed in Section 5.2.2 the imposition of the export stimulus in MARCO-UK leads to a feedback loop causing high rate of utilisation of capacity (high Y/L and Y/K) as well as a sharp increase in profits, which immediately stimulates a very substantial 6.3% increase in investment (double the stimulus in the FNW variant of the CGE) which in turn stimulates GDP and consumption even more. Therefore, the short-term stimulus to GDP goes beyond the increase in exports and is even bigger than the long-term effect of the export shock.

The increase in employment is also higher in the short run (1.3%) than in the long run (0.4%) in MARCO-UK as the labour productivity improvements triggered by increased capital stocks have not materialised by that point. Overall, the expansion is greatest in the short-run in MARCO-UK, for an export stimulus, whereas it is greatest in the long run within all the configurations of UK-ENVI.

6.3 Price effects

As noted previously, prices play a rather different role in MARCO-UK and UK-ENVI. In response to the export shock MARCO-UK shows only very small changes to CPI both in the

[16] In fact, the impact of a labour productivity shock on employment while generally ambiguous, is typically found to be positive in the long run. See Ross et al., (2018c) for a discussion of the impacts of improvements in labour productivity.

long run (-0.43%) and in the short run (0.15%). The stimulus to exports is not affected by prices, as it is effectively set exogenously in the set-up of the MARCO-UK scenario.

In contrast, changes in competitiveness are central to the determination of trade flows in UK-ENVI. In the CGE model, prices behave very differently across different model configurations, but in all cases they move simultaneously to equilibrate the demand and supplies of goods and factors (although this process is impacted by the presence of imperfect competition in the labour market). However, prices do not fall in the long run under any of the models. The limiting case, provided by the fix-wage models, is of no changes in prices, but only in the long run. Over this period, labour supplies are effectively infinitely elastic and capital stocks are fully adjusted at an assumed unchanged interest rate. It is "as if" capital as well as labour is in infinitely elastic supply and so there is ultimately no upward pressure on prices in response to the export stimulus. However, prices are not fixed in the fix-wage models: as is clear from the short-run results (see below) prices can and do change in the short-run, and are pushed up by the stimulus to demand given the (capital stock) constraint on supply, with the CPI rising by 0.92% under FNW and 1.09% under the FRW. Of course, the distribution of the impact of the stimulus to demand between prices and quantities is least favourable when supply constraints are greatest – under ELS: here the CPI ultimately rise by 1.29% and the real wage by 1.43%, and the impact on GDP is limited to 0.23% (which is a reflection of changing sectoral structure).

6.4 Energy and emission effects

The consumption of final energy increases across both models (including all UK-ENVI configurations) both in the short and long run. In the long run the magnitude of the increase generally reflects the change in GDP so that MARCO-UK shows the biggest increase in energy consumption (3.5%) followed by the UK-ENVI FRW-FNW model (2.53%), the BRW (1.72%) and ELS (1.21%).

However, the increase in energy use is not solely a result of increased GDP, because the energy intensity of the economy also increases across all models in the long run. In the UK-ENVI models the increase in energy intensity is largely the result of changes in the level of outputs and their distribution across sectors. Those sectors that benefit most from the stimulus to exports are, relatively more energy intensive. In MARCO-UK the increased energy intensity is a result of the increased capital intensity of the economy. While the increase in capital intensity has beneficial effects on labour productivity, it also translates into larger requirements for useful exergy. A key feature of the MARCO-UK model is the endogenous efficiency for the transformation of final energy to useful exergy (EXEFF_FU). Due to higher investment, EXEFF_FU increases relatively to the baseline. However, this increase is not sufficient to offset the increase in useful exergy consumption, so that final energy use still increases. This pattern is a reflection of UK trends over the past 60 years, in which thermodynamic efficiency improvements have generally not been able to outpace economic growth, so that energy consumption has increased slightly despite significant improvements in the energy intensity of the economy. There is some evidence that increases in thermodynamic efficiency might even have been a contributor to higher growth rates through a macroeconomic rebound effect (Brockway et al. 2017, Sakai et al. 2019). Energy efficiency – in both production and consumption – is typically treated as exogenous in UK-ENVI. Again, while increased investment impacts energy *intensity* within UK-ENVI, technical energy *efficiency* is unaffected. If there was compelling evidence of a causal link from investment to energy intensity it could be built into UK-ENVI.[17]

For the CGE models the pattern in the short run is similar to the long run in the sense that both energy consumption and energy intensity increase in all models. The fix-wage models are associated with the biggest increases in GDP and in energy. For all the CGE model configurations energy use increases in the long-run compared to the short-run, as typically does energy intensity (except for the FNW case). In MARCO-UK the short-run effect is somewhat different. Energy consumption increases by 1.03% but this is much smaller than the long-run effect (3.50%) and energy intensity of the economy even falls. The reason for the fall of energy intensity in the short-run is a lagged response built into the function determining useful exergy use in the MARCO-UK model. This presents the assumption of spare capacity in the economy, so that production can be increased somewhat without increasing the inputs in useful exergy and final energy in an equal manner.

Neither UK-ENVI nor MARCO-UK feature a detailed representation of the energy system to estimate the carbon emissions associated with changes in energy use. Hence, the MARCO-UK estimates carbon emissions using an IPAT approach that is drawing on the primary energy intensity of the economy and estimated statistically from historical trajectories.

However, while not providing the detail of energy systems models, UK-ENVI does separately identify energy producing sectors and energy demands and supplies are modelled as indicated above, with energy prices "clearing" markets. Changes in relative prices impact the composition of economic activity and therefore energy use and emissions. Policy interventions that impact the price of carbon (such as a carbon tax) change the carbon-intensity of sectoral outputs, and, of course, impact aggregate emissions (see Allan et al., (2018) for a more detailed discussion).

In the simulations reported here, the price of carbon is unaffected. This means that CO_2 emissions broadly increase in line with energy use as a result of the export shock in both MARCO-UK and UK-ENVI. Industrial territorial emission increase in UK-ENVI by 1.6% in the long run, and by 0.43% in the short-run, in the BRW closure. In MARCO-UK territorial CO_2 emissions increase by 2.84% in the long run and 1.43% in the short run. MARCO-UK also estimates consumption-based CO_2 emissions, which increase even more strongly than territorial emissions, namely 2.14% in the short run and 3.24% in the long run.

A central interest in the present paper is on the incremental change in emissions that is likely to arise from export policy actions alone. This identifies the potential additional challenge made to meeting the Government's emissions targets that is solely attributable to export policy. Whilst emissions increase here across all models, the scale is typically modest relative to the decarbonisation that has occurred over the last two decades. This said, other things being equal some adjustment in energy policy at the margin would be required to offset the additional emissions associated with an expansion in exports.

[17] The resultant analysis would be a combination of that presented here and the analysis of energy efficiency changes presented in Ross et al., (2018d).

6.5 Policy implications

The results we obtain from both models suggest that there are potential tensions between economic and energy policy goals, because a successful pursuit of an export-stimulating strategy could increase the energy intensity of the UK economy. In the case of no further progress in the decarbonisation of the energy supply, any increase in energy demand would increase the UK's carbon emissions. However, this is unlikely to be the case, because there will be ongoing efforts to reduce the carbon intensity of energy to achieve the UK climate change targets, as set out in the Clean Growth Strategy (HM Government 2017a). Nevertheless, an increase in energy demand will add to the challenge of achieving the climate change targets in the UK, as it will require additional capacity of low-carbon energy supply. The fact that both of the models, although being very different, arrive at similar results underlines the robustness of our conclusion. One option to mediate any adverse impacts of an export strategy on energy intensity would be to step up efforts to increase energy efficiency throughout the economy. However, there is evidence that macroeconomic rebound effects can reduce the effectiveness of efficiency improvements as a strategy for reducing energy demand, by partially cancelling out reductions in energy use with increases in other places. The potential for such rebound effects has been shown using CGE models (e.g Hanley et al. 2009; Lecca et al., 2014a) as well as econometric studies (Brockway et al. 2017) and has also been demonstrated using the MARCO-UK model (Sakai et al. 2019). Ross et al (2018d) use the UK-ENVI model to analyse the consequences of improvements in energy efficiency in consumption and production, which could mitigate and even offset the adverse emissions impacts of a successful export strategy.

While the tension between exports and carbon emissions is a feature of both the models, our results also suggest that the specific impacts of an export stimulus on energy consumption can take a variety of forms which are strongly dependent on the wider macroeconomic circumstances and the economic assumptions of the models. Here the two models offer some complementary strengths in exploring the range of ways in which the economic and energy system are connected.

A key strength of UK-ENVI is the detailed representation of demand-supply interactions in internal and export markets. One key result is that higher wages could inhibit the real effects of the export stimulus because they make the UK less competitive. This is a mechanism that is not modelled in MARCO-UK. In the extreme case of a fixed labour supply, the real stimulus to export sectors is much reduced, and labour is simply reallocated across sectors (although this does increase GDP slightly). The UK's Industrial Strategy (HM Government 2017b) aspires to increase both higher exports and higher wages, but the UK-ENVI results suggest that there may be a trade-off between them given the negative effects of reduced competitiveness on exports.

The trade-off is not inevitable, however. First, real wages have actually fallen over the decade since the financial crash, so it may be that there is some scope for further expansion of the economy without adverse competitiveness effects, but again this would depend on wages continuing to be comparatively depressed (as in the fix wage variants of UK-ENVI). However, there are signs that real wage growth is now beginning to appear, and is being welcomed following a long period of wage stagnation. This suggests that perhaps the scope for further fix-wage growth is limited. Furthermore, wages could potentially be influenced by post-Brexit changes to the UK immigration regime.

Second, there may be some scope for stimulating labour productivity simultaneously with exports. A key feature of the MARCO-UK model is the endogenous relationship between capital and labour productivity. The econometric equations describe how investment, capital stocks, labour productivity, and energy use interact to shape the growth trajectory of the UK economy in line with historical developments. Based on these historical relationships MARCO-UK suggests that the export shock could lead to increases in investment and capital stocks which would reduce the need for labour. Such labour productivity improvements would weaken the trade-off between wages and export growth. However, as a result the boost to employment would be much lower, highlighting a different trade-off, namely between employment and labour productivity. Increased investment does not automatically stimulate labour productivity in UK-ENVI. If there was compelling evidence for such a link its incorporation within UK-ENVI would again narrow the gap between the models by stimulating output further and inhibiting price rises in response to the export stimulus.[18,19]

There is evidence that exporting firms tend to be more productive, but the link may depend on the precise policies pursued to stimulate exports. In order to avoid adverse competitiveness effects of any increases in wages, accompanying stimuli to productivity may be required. However, while that is clearly a preferred route to the continuation of wage stagnation as a means of avoiding adverse competitiveness pressures, past experience suggests it is not that easy to stimulate productivity growth. In addition, there may be some scope for limiting any trade-off between exports and wages through judicious sectoral targeting of export and productivity enhancements. The sectoral detail within UK-ENVI would allow a systematic analysis of such initiatives, but it is not pursued here.

Finally, UK-ENVI has considerably more detail on government revenues and expenditures, and automatically tracks changes in these. Similarly, impacts on the distribution of income are identified (albeit only across income quintiles). Currently, MARCO-UK provides much less detail on government revenues and expenditures and income distribution. However, this does not reflect a difference in modelling approaches, but instead the comparatively earlier stage of development of the MARCO-UK model. We plan to include a more detailed representation of the government sector and income distribution in future versions of the MARCO-UK model.

7 Summary and Conclusion

Meeting the UK's carbon targets, while also pursuing a successful industrial strategy requires understanding of the interactions between the economic and the energy system. The analysis we provide in this study contributes to this understanding by comparing the interconnections between the economy and key elements of the energy system using two macroeconomic

[18] For a full analysis of the effects of a stimulus to productivity in UK-ENVI see Ross et al., (2018c). If productivity were automatically linked to investment, the analyses of that paper and the present one would need to be combined.
[19] There is some evidence to suggest that there is a positive correlation between firms that export and higher productivity, and micro-evidence could be used to specify a link. Note that in MACRO-UK, any stimulus to demand – not just export demand - generates a rapid investment response.

modelling approaches, a computable general equilibrium (CGE) model and a macroeconometric (ME) model.

We only consider a simple stimulus to demand in the current analysis because it facilitates analysis of an identical disturbance to both models without the added complication of comparing two models as well as different disturbances. In both models we analyse a stimulus to demand from an increase in exports arising from a successful export strategy as motivated by the UK Industrial Strategy (HM Government 2017b). This is a disturbance that both models find it comparatively straightforward to address.

The qualitative results of the export stimulus are similar across all models in that GDP and employment are always stimulated. In this sense, the results are reassuring for the UK's Industrial Strategy that emphasises export promotion. However, the models also find that total energy use and CO_2 emissions increase, and so does the energy intensity and emissions intensity of GDP. This identifies the potential additional challenge made to meeting the Government's emissions targets that is solely attributable to export policy. Whilst emissions increase here across all models, the scale is typically modest relative to the decarbonisation that has occurred over the last two decades. This said, other things being equal some adjustment in energy policy at the margin would be required to offset the additional emissions associated with an expansion in exports. The results highlight the interdependence of the energy and economic systems and shows that there are benefits to coordinating strategic initiatives, to tackle carbon emissions, as envisaged in the UK's Clean Growth Strategy, simultaneously with stimulating economic activity.

The differences across the models are informative, reflecting in part differences in the underlying macroeconomic vision of the UK economy, from the post-Keynesian model, MARCO-UK, through "Keynesian" fix-wage variants of UK-ENVI to the extreme neoclassical vision of the exogenous labour supply configuration of UK-ENVI. We show that it can be useful to have a range of energy-economy models for exploring the different links between the economy and key elements of the energy system, and for identifying the circumstances in which each model is most likely to be directly applicable.

As a CGE model, UK-ENVI focuses on the general equilibrium of the economy, and how it is affected by disturbances on the demand and/or supply side, such as the export stimulus we analyse here. Its key strength lies in the analysis of how such disturbances change the balance between supply and demand across all markets in the economy. For example, in our analysis this provides valuable insights into the transmission mechanisms of the export stimulus through the UK economy and how it creates shifts in the composition of the economy as well as changes in prices, wages and incomes. A key difference from the macroeconometric MARCO-UK model is that it is straightforward to explore the impact of supply-side constraints in UK-ENVI (and CGEs in general) given its inclusion of a fully specified supply side (which dominates macroeconomic behaviour in some circumstances). For example, the effects of restrictions on any factor of production (capital, labour, materials, energy) can be analysed straightforwardly in UK-ENVI, as can policies that impact at least partially on the supply side, such as tax changes (e.g. Lecca et al, 2014b). This is more challenging within a macroeconomic model such as MARCO-UK, because the underlying macroeconomic vision assumes a limited importance for supply constraints. While the simulations of UK-ENVI reported here assume that factor *efficiencies* are exogenous (although factor *intensities* are endogenous responding, inter alia, to relative price changes), UK-ENVI can be used to analyse changes in e.g. labour and energy efficiency (e.g. Turner &

Hanley, 2011). If these were to be endogenised their impact would come through substitution and competitiveness effects, which are not part of the focus of MARCO-UK.

As a ME model, MARCO-UK is based on econometric relationships that are derived from historical data and describe the relationships between economic variables, such as wages, investment or capital stocks. The interplay between the variables, as described in the econometric equations, then produces endogenous projections of economic growth and other economic variables, without assuming the optimising behaviour by agents. Its key strength therefore lies in the analysis of how disturbances change the trajectory of the UK economy over time, based on the econometric relationships. For example, in our analysis it provides insights into how an export stimulus affects investment and therefore labour productivity, which in turn has implications for wages and employment.

Supply-side variables, such as the efficiency of production factors, play very different roles in the two models. While they directly influence production through the choices of producers in UK-ENVI, they influence production indirectly through their effects on demand in MARCO-UK. Hence, it would be useful to compare the impact of factor efficiency changes, such as labour or energy efficiency, within the two models; it seems likely that there would be greater disparity in outcomes than is apparent for demand-side disturbances, such as the export stimulus.

In addition to these fundamental differences in modelling approaches, an important advantage of UK-ENVI is its detailed sectoral disaggregation. While the export stimulus considered here is an across-the-board "macro" disturbance, a focus on individual sector's export performance would not be directly possible in MARCO-UK as it is currently formulated (though further disaggregation is possible), though it is in UK-ENVI. Similarly, UK-ENVI automatically tracks the impacts of disturbances on households by income quintile so that distributional issues can be addressed.[20]

MARCO-UK provides less detail, which is partially due to the fact that its development only started recently and more disaggregation will be included in future versions of the model. However, the estimation of ME models requires consistent dataset with time-series data for all variables. While the statistical estimation of the model equations is a key strength of the MARCO-UK model, it makes it more challenging to add more detail.

In the context of energy-economy modelling, our analysis suggests that it is advantageous to have a mix, or portfolio, of energy-economy models with each having comparative advantages depending on: prevailing circumstances, notably the state of the economy (as reflected in any excess capacity); the time period of interest and the nature of the question being addressed.

In terms of policy, there is evidence that an industrial strategy aimed at 'across the board' export led growth may produce a trade-off with the achievement of economic and carbon emission targets in the UK. Given the urgency of climate change mitigation, this evidence highlights that the development of any economic policy needs to consider the possible implications for energy use and carbon emissions. On the flipside, any policies for climate change need to make sure that they are compatible with important economic objectives,

[20] Other versions of the CGE model contain a more detailed treatment of e.g. the labour market, households, government and taxation, and assets provided by nature (i.e. natural capital).

such as the provision of high quality jobs across all regions of the UK. A potential avenue for future research could extend the analysis in this working paper by considering whether it is possible to identify industries where an increase in exports has positive economic consequences but without simultaneously increasing energy- or emissions-intensities. Of course, in the spirit of the above, such an analysis should not only be based on the current energy and emissions intensity of different industries, but should also take into account the unfolding changes in the energy system and their impact on different industries.

Ultimately, achieving both our environmental and economic objectives requires a holistic strategy that considers both objectives together. While it increases the complexity of the challenges faced by policy makers and researchers, the coordination of industrial and energy and environmental policies holds the promise of helping to overcome any trade-offs and exploit any complementarities, resulting in potentially significant policy gains.

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Appendix A: MARCO-UK results in absolute terms

Table A1: Absolute values of key variables in the MARCO-UK model in the baseline and export scenarios.

Variable	Symbol	Unit	Baseline		Export scenario	
			Avg. 2014-2016	2050	Avg, 2014-2016	2050
GDP	Y	£bn	1781	3300	1836	3386
Consumption	C_T	£bn	1130	2710	1153	2767
Investment	I	£bn	307	398	326	403
Government expenditure	G	£bn	363	731	363	731
Total imports	M	£bn	587	2721	603	2806
Total exports	X	£bn	569	2181	597	2290
Total employment	L	million employees	30.68	39.6	31.1	39.8
Unemployment rate	UR	%	6.70	2.25	5.62	2.15
Profit (Capital income)	YF	£bn	684	1167	716	1208
Wage income	W	£bn	879	1727	895	1762
Hourly wages	W_HOUR	£	14.10	21.04	14.28	21.33
Government income	YG	£bn	219	405	225	415.517
Government budget	YG-G	£bn	-144	-326	-137	-316
Capital service intensity	K_SERV/Y	£bn/£bn	5.09	5.14	5.00	5.17
Useful exergy intensity	UEX_TOT/Y	PJ/£bn	0.648	0.302	0.642	0.306
Labour intensity	L/Y	million employees/£bn	0.0172	0.0120	0.0169	0.0117
Final energy intensity	FEN_T/Y	TJ/£m	3.29	1.39	3.23	1.41
Total final energy consumption	FEN_T	PJ	5858	4598	5919	4759
Total useful exergy consumption	UEX_TOT	PJ	1154	997	1178	1036
Energy use by households	FEN_C	PJ	1773	1576	1804	1623
Energy use by industry sectors	FEN_IND	PJ	975	441	986	450
Energy use by non-industry sectors	FEN_OTH	PJ	3111	2581	3129	2686
CO_2 emissions (territorial)	CO2_TERR	Mt	531	380	538	391
CO_2 emissions (consumption-based)	CO2_CONS	Mt	716	683	731	706
Output of industrial sectors	IND_T	£bn	349	372	356	376
Output of non-industrial sectors	OTH_T	£bn	1433	2928	1480	3010
CPI	CPI	-	107.7	156.9	107.9	156.2
General price of energy	CPI_E	-	116.4	264.2	116.0	252.1

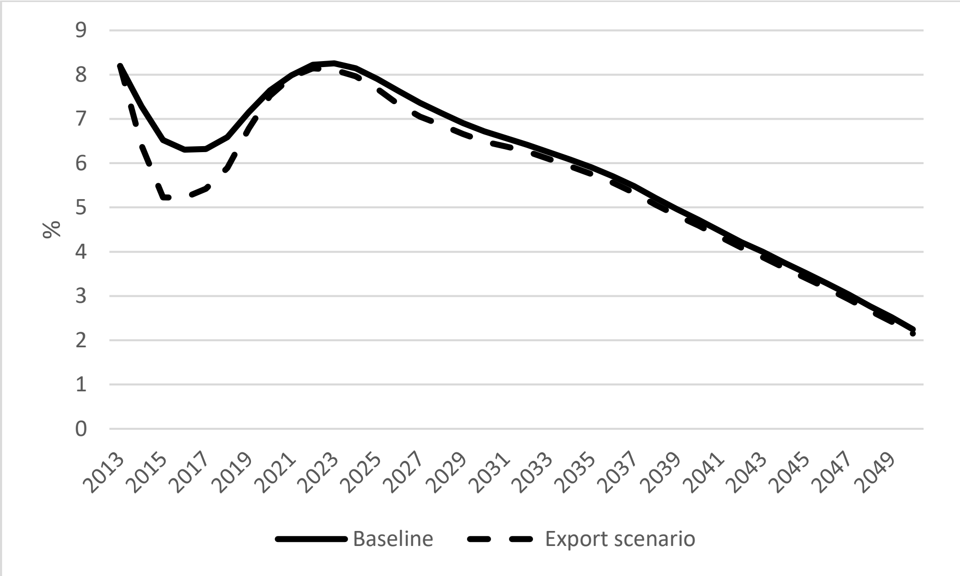


Figure A1: The UK unemployment rate in the UK in the Baseline and Export scenario in the MARCO-UK model

Appendix B: Sensitivity analyses of MARCO-UK results

In addition to the main analysis presented in the paper, we implemented a range of alternative scenarios in the MARCO-UK model. These alternative scenarios test the sensitivity of the results to changes in the set-up of export scenario or the MARCO-UK model. The alternative scenarios are:

Scenario name	Export Scenario	MARCO-UK Model
Main analysis	5% exogenous increase in exports in years 2014-2050 (see section 3)	Full model (see section 4.2)
Fixed energy prices	Same as main analysis	Energy prices are fixed at baseline values
Fixed government income	Same as main analysis	Government income is fixed at baseline values and does not adjust in line with GDP
Export ramp	Exports are increased linearly from 0% in 2013 to 5% in 2023	Same as main analysis

Table A2 and Table A3 outline the short-term and long-term results for the different scenarios, while Figures A2-A5 illustrates that the adjustment path in the export ramp scenario is smoother than in the main analysis scenario.

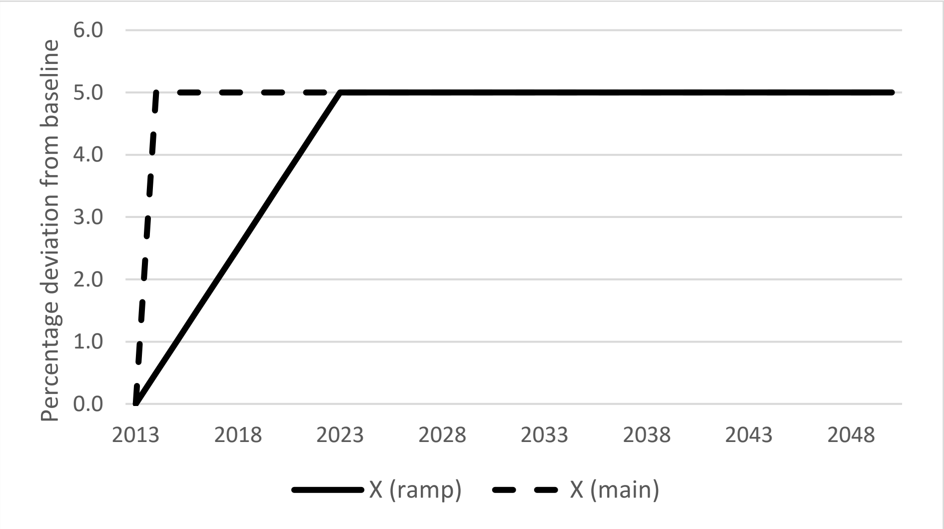


Figure A2: The export shock in the export ramp scenario compared to the main analysis scenario.

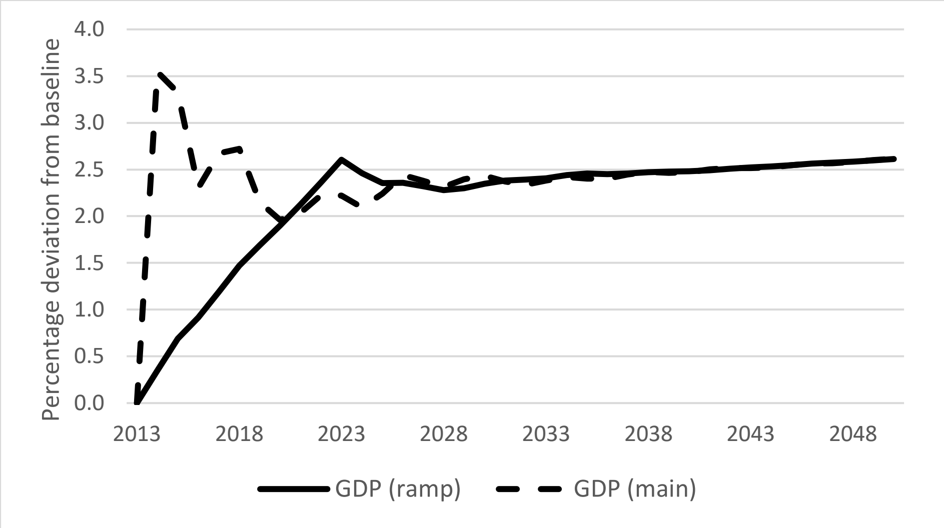


Figure A3: Impact of the export shock on GDP in the export ramp and the main analysis scenario.

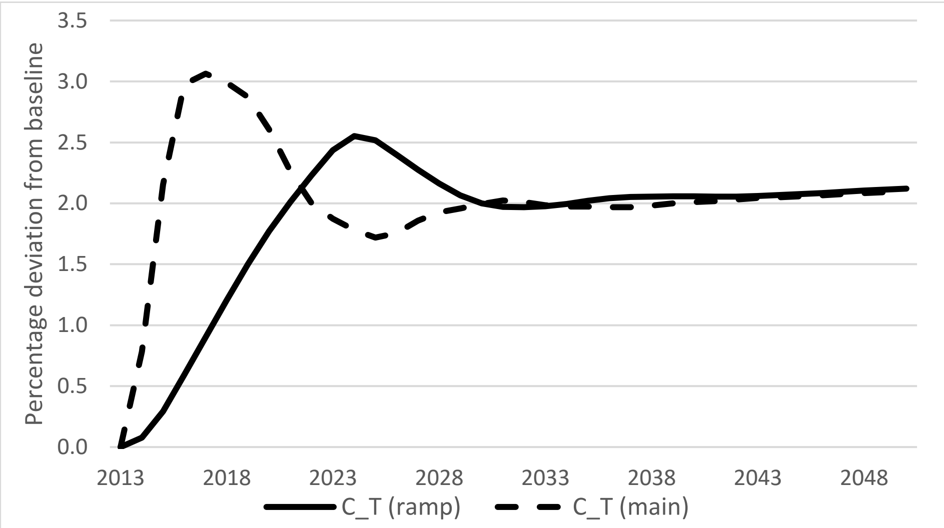


Figure A4: Impact of the export shock on consumption in the export ramp and the main analysis scenario.

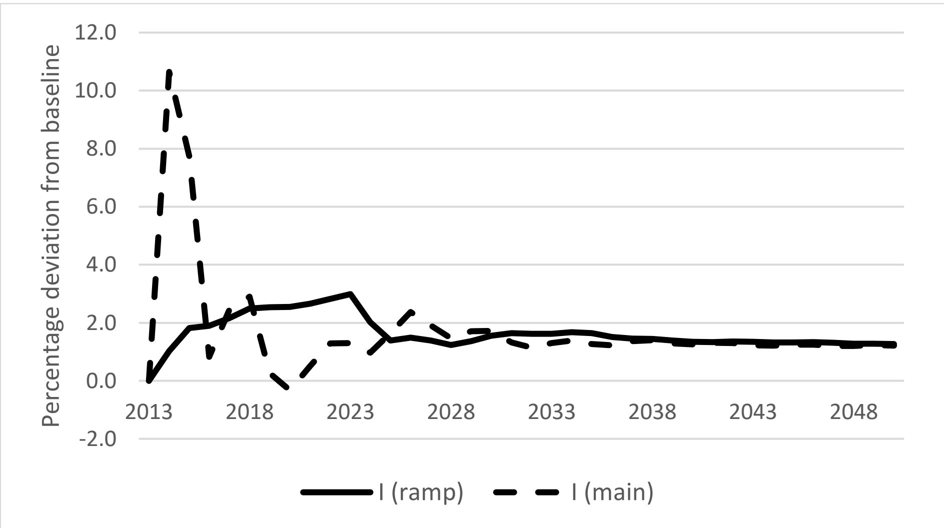


Figure A5: Impact of the export shock on Investment in the export ramp and the main analysis scenario.

Table A2: Long-term effects of an increase in exports for some key variables in the MARCO-UK model and for different scenarios. Results are presented as % deviation from the baseline scenario.

		Long term (year 2050)			
Variable	Symbol	Main analysis	Fixed energy prices	Fixed gov. income	Export ramp
GDP	Y	2.61	2.58	2.64	2.61
Consumption	C_T	2.10	2.18	2.12	2.12
Investment	I	1.22	1.18	1.42	1.27
Government expenditure (exogenous)	G	0.00	0.00	0.00	0.00
Total imports	M	3.11	3.22	2.94	3.14
Total exports	X	5.00	5.00	5.00	5.00
Total employment	L	0.47	0.46	0.39	0.49
Unemployment rate (pp difference)*	UR	-0.10	-0.09	-0.01	-0.11
Profit (Capital income)	YF	3.51	3.46	4.60	3.44
Wage income	W	2.01	1.98	1.99	2.05
Hourly wages	W_HOUR	1.34	1.41	1.19	1.39
Government income	YG	2.61	2.58	0.00	2.61
Government budget	YG-G	-3.25	-3.20	0.00	-3.24
Capital service intensity	K_SERV/Y	0.44	0.45	0.80	0.37
Useful exergy intensity	UEX_TOT/Y	1.27	1.27	1.46	1.22
Labour intensity	L/Y	-2.09	-2.07	-2.19	-2.07
Final energy intensity	FEN_T/Y	0.86	0.70	0.98	0.81
Total final energy consumption	FEN_T	3.50	3.30	3.65	3.45
Total useful exergy consumption	UEX_TOT	3.92	3.88	4.14	3.87
Energy use by households	FEN_C	2.97	2.65	3.03	2.97
Energy use by industry sectors	FEN_IND	2.09	1.88	2.19	2.07
Energy use by non-industry sectors	FEN_OTH	4.05	3.93	4.27	3.97
CO_2 emissions (territorial)	CO2_TERR	2.84	2.74	2.92	2.82
CO_2 emissions (consumption-based)	CO2_CONS	3.24	3.21	3.30	3.24
Output of industrial sectors	IND_T	1.04	1.04	1.13	1.03
Output of non-industrial sectors	OTH_T	2.81	2.77	2.83	2.81
CPI	CPI	-0.43	0.19	-0.45	-0.44
General price of energy	CPI_E	-4.60	0.00	-4.80	-4.54

* Absolute difference between UR in the export scenario and the baseline scenario

Table A3: Short-term effects of an increase in exports for some key variables in the MARCO-UK model and for different scenarios. Results are presented as % deviation from the baseline scenario.

		Short term (average 2014-2016)			
Variable	Symbol	Main analysis	Fixed energy prices	Fixed gov. income	Export ramp
GDP	Y	3.05	3.06	3.19	0.66
Consumption	C_T	2.00	2.05	2.13	0.33
Investment	I	6.33	6.37	6.99	1.59
Government expenditure (exogenous)	G	0.00	0.00	0.00	0.00
Total imports	M	2.75	2.82	2.94	0.45
Total exports	X	5.00	5.00	5.00	1.01
Total employment	L	1.33	1.33	1.38	0.26
Unemployment rate (pp difference)*	UR	-1.09	-1.09	-1.13	-0.21
Profit (Capital income)	YF	4.62	4.65	5.74	1.11
Wage income	W	1.83	1.83	1.97	0.30
Hourly wages	W_HOUR	1.29	1.30	1.35	0.20
Government income	YG	3.05	2.58	0.00	0.66
Government budget	YG-G	-4.63	-4.65	0.00	-1.00
Capital service intensity	K_SERV/Y	-1.86	-1.87	-1.88	-0.44
Useful exergy intensity	UEX_TOT/Y	-1.02	-1.03	-1.06	-0.27
Labour intensity	L/Y	-1.69	-1.69	-1.77	-0.39
Final energy intensity	FEN_T/Y	-1.98	-2.08	-2.06	-0.47
Total final energy consumption	FEN_T	1.03	0.94	1.08	0.18
Total useful exergy consumption	UEX_TOT	2.02	2.02	2.11	0.38
Energy use by households	FEN_C	1.76	1.67	1.85	0.30
Energy use by industry sectors	FEN_IND	1.10	1.08	1.16	0.20
Energy use by non-industry sectors	FEN_OTH	0.59	0.49	0.62	0.10
CO_2 emissions (territorial)	CO2_TERR	1.43	1.39	1.50	0.25
CO_2 emissions (consumption-based)	CO2_CONS	2.14	2.11	2.26	0.37
Output of industrial sectors	IND_T	1.96	1.98	2.13	0.45
Output of non-industrial sectors	OTH_T	3.31	3.33	3.45	0.71
CPI	CPI	0.15	0.19	0.16	0.02
General price of energy	CPI_E	-0.37	0.00	-0.39	-0.06

* Absolute difference between UR in the export scenario and the baseline scenario

Appendix C: Estimated parameters of the MARC0-UK model

The econometric equations are estimated using Ordinary Least Squares (OLS), which is common in macroeconometric modelling. In some cases, where it is found that the involved variables share common long-term equilibrium relationships using the Johansen cointegration test, long-run and short-run specifications are estimated following the Engle-Granger approach (Engle & Granger 1987). A long-term specification is estimated using the variables in levels (i.e. without differencing) and without including time lags. Some of these specifications present auto-correlation (i.e low Durbin-Watson stats) and heteroscedasticity in the residuals, but they are not used directly in the model. Only the residuals from these equations are used by introducing them into the short-term specifications. Short-term specifications are then estimated using the variables expressed in first differences including lags for all variables. The residuals from the long-term specifications are then incorporated, but lagged one time period, resulting in an error correction term (ECT). The estimated parameter of the ECT must be significant and negative, in which case the existence of a cointegrating relationship can be confirmed. Finally, the residuals from the short-term specification are tested for autocorrelation, heteroscedasticity, serial correlation and normality to ensure the robustness of the estimation. The residuals are also tested for the presence of unit roots and confirm that they are considered as 'white noise'.

An important issue is that econometric simultaneous equation systems often violate the assumption of no correlation between the residuals of endogenous variables and the independent variables. Such violation occurs when endogenous variables are also treated as exogenous in other equations, giving rise to simultaneity bias. Correction can be achieved using two-stage least squares (TSLS) rather than OLS solution methods. However, TSLS methods can yield less accurate simulations due to data errors or sampling bias (Solomon & Rubin 1985). Moreover, due to the size of the model, TSLS is not feasible due to the large number of instrumental variables and the use of cointegration techniques. Therefore, we estimate the equations using OLS following the procedures suggested by Brillet (2016).

Dummy variables are used in some equations, acknowledging that their inclusion is restricted by the degrees of freedom in the data, in order to capture certain periods in the UK economy characterised by unusual movements in the time-series data. Several variables present signs of structural break. When estimating an equation, the Chow structural breakpoint test is applied to determine the year when the trends change. A dummy variable is then included in order to capture the beak and avoid heteroscedasticity in the residuals. Structural breaks were found mainly for 1976 and 1982, years of economic crisis. Moreover, a dummy for the year 2009 was often used to capture the effects of the global financial crisis. To avoid repetition, dummy variables are not presented in the estimations below. However, they constitute an important element in the solution of the model.

All the variables are expressed in logs, except when noted.

Consumption of non-energy goods

Long-term specification:

Dependent variable log(CNE)

Variables	Estimated coefficients	t-stats
Constant	-3.8195***	-4.3044
log(YD)	0.8192***	11.6631
log(UEX_TOT)	0.1868**	2.0455
log(W)	0.2644***	3.6330
R^2	0.9966	
DW	0.5550	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(CNE)

Variables	Estimated coefficients	t-stats
Error Correction Term (ECT)	-0.3889***	-4.3860
Δlog(CNE(-1))	0.4610***	4.5834
Δlog(CNE(-2))	-0.2878***	-3.2377
Δlog(YD)	0.5494***	5.8016
Δlog(UEX_TOT)	0.1512**	2.5014
Δlog(W)	0.3426***	3.0243
R^2	0.8391	
DW	2.0325	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Investment

Long-term specification:

Dependent variable log(I)

Variables	Estimated coefficients	t-stats
Constant	-6.6667***	-3.9349
log(PROFIT)	0.8180***	4.9451
log(Y)-log(K_NET)	1.7091***	5.7128
log(Y)-log(UEX_TOT)	-0.2498	-1.6765
log(Y)-log(L)	-0.4969*	-2.0053
R^2	0.9630	
DW	1.1333	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(I)

Variables	Estimated coefficients	t-stats
ECT	-0.4093***	-3.0185
Δlog(PROFIT)	0.3817**	2.0803
Δ(log(Y)-log(K_NET))	2.7435***	5.5522
Δ(log(Y(-1))-log(UEX_TOT(-1)))	0.4232*	1.8429
Δ(log(Y(-2))-log(L(-2)))	-0.7138**	-2.4244
R^2	0.8361	
DW	1.7681	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Exports

Long-term specification:

Dependent variable log(X)

Variables	Estimated coefficients	t-stats
log(Y_RW)	0.2116*	1.8375
log(PX)	-0.0935***	-3.2339
log(UEX_TOT)	0.4348*	1.8793
time trend	0.0352***	29.4273
R^2	0.9927	
DW	0.7340	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(X)

Variables	Estimated coefficients	t-stats
ECT	-0.4800***	-5.6523
Δlog(X(-1))	0.1467	1.6234
Δlog(Y_RW)	0.3784**	2.5134
Δlog(PX)	0.1303**	2.2218
log(UEX_TOT)	0.2300	1.5721
R^2	0.6365	
DW	1.7520	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Imports

Long-term specification:

Dependent variable log(M)

Variables	Estimated coefficients	t-stats
Constant	-14.7779***	-6.6870
log(C_T)	1.4765***	14.0289
log(Y_RW)	0.2772**	2.1734
log(PM)	-0.1143***	-4.0545
R^2	0.9978	
DW	1.2035	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(M)

Variables	Estimated coefficients	t-stats
ECT	-0.7850***	-7.0120
Δlog(M(-2))	-0.2162***	-3.2239
Δlog(M(-3))	-0.0832	-1.4058
Δlog(C_T)	1.3461***	9.1013
Δlog(Y_RW)	0.6683***	4.9923
Δlog(E_INDEX_REAL(-3))	-0.0738*	-1.7420
R^2	0.8836	
DW	1.9441	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Industrial non-energy value added

Long-term specification:

Dependent variable log(IND_NE)

Variables	Estimated coefficients	t-stats
Constant	6.2425***	5.5430
log(I)	0.1784***	3.2194
log(UEX_TOT)	0.2956***	3.1020
R_REAL	0.0066***	5.3448
time trend	0.0022**	2.0978
R^2	0.9532	
DW	1.0760	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(IND_NE)

Variables	Estimated coefficients	t-stats
ECT	-0.4663**	-2.6534
Δlog(IND_NE(-2))	0.2493**	2.2046
Δlog(I)	0.2619***	6.1465
Δlog(UEX_TOT(-1))	0.1924*	1.9986
Δ(R_REAL)	0.0022	1.4154
R^2	0.7094	
DW	1.9006	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Wage income

Dependent variable log(W)

Variables	Estimated coefficients	t-stats
Constant	-4.8482***	-5.6489
log(W(-1))	0.5627***	9.1347
log(YF(-1))	0.0702***	2.8359
log(W_HOUR)	0.3455***	7.5483
log(CPI)	-0.0436***	-5.1839
log(HL)	0.6283***	7.0222
log(HL(-1))	-0.3045***	-3.6446
R^2	0.9995	
DW	1.9137	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Disposable income

Long-term specification:

Dependent variable log(YD)

Variables	Estimated coefficients	t-stats
Constant	4.1731***	3.0289
log(W)	0.4419***	4.9118
log(NW)	0.2138***	4.5010
Time trend	0.0100***	3.4166
R^2	0.9914	
DW	0.3380	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(YD)

Variables	Estimated coefficients	t-stats
ECT	-0.1636*	-1.9870
Δlog(YD(-1))	0.3086***	3.0816
Δlog(W)	0.4360***	3.2382
Δlog(NW)	0.1164**	2.4487
R^2	0.5634	
DW	1.7527	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Net wealth

Dependent variable log(NW)

Variables	Estimated coefficients	t-stats
log(NW(-1))	0.8903***	22.6930
Δ(UR)	-0.0196**	-2.4891
log(YD)	0.1269***	2.8744
R^2	0.9938	
DW	1.7252	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Labour force

Dependent variable log(LF)

Variables	Estimated coefficients	t-stats
log(LF(-1))	1.3720***	12.5147
log(LF(-2))	-0.5117***	-4.8660
log(Y)	0.0203***	3.7328
log(POP)	0.1050***	3.0545
R^2	0.9962	
DW	1.8470	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Labour supply

Long-term specification:

Dependent variable log(L)

Variables	Estimated coefficients	t-stats
Constant	5.4259***	8.3887
LOG(Y)	0.5694***	10.6527
LOG(UEX_TOT)	-0.1177*	-1.9264
LOG(K_SERV)	-0.1808***	-6.1863
R^2	0.9439	
DW	0.5616	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(L)

Variables	Estimated coefficients	t-stats
ECT	-0.2802***	-4.9165
DLOG(L(-1))	0.5263***	7.2403
DLOG(Y)	0.3190***	7.8693
DLOG(UEX_TOT)	-0.0599*	-1.9645
DLOG(K_SERV(-1))	-0.1151***	-4.1236
R^2	0.8747	
DW	1.8900	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Consumer price index

Long-term specification:

Dependent variable log(CPI)

Variables	Estimated coefficients	t-stats
Constant	-1.2706***	-18.9318
log(CPI_E)	0.1307***	4.5023
log(PM)	1.1823***	26.6341
log(W)-log(Y)	-0.3321**	-2.5997
R^2	0.9981	
DW	1.2484	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(CPI)

Variables	Estimated coefficients	t-stats
ECT	-0.2970***	-3.3175
Δlog(CPI_E)	0.0855*	1.8709
Δlog(PM)	1.1891***	15.4800
Δlog(W(-4))- Δlog(Y(-4))	0.3004**	2.6977
Δ(E_INDEX_REAL)	0.0011***	4.5750
R^2	0.9336	
DW	1.8968	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Consumer price index (energy)

Dependent variable log(CPI_E)

Variables	Estimated coefficients	t-stats
Constant	1.1140***	11.4422
log(CPI_E(-1))	0.6842***	9.2486
log(CPI_E(-2))	-0.2215***	-2.8588
log(P_EN_C(-2))	0.0574	1.2811
log(P_EN_IND)	0.2004***	8.8205
log(P_EN_OTH)	0.2191***	7.9590
R^2	0.9993	
DW	2.2372	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Export prices

Dependent variable log(PX)

Variables	Estimated coefficients	t-stats
log(PX(-1))	0.6706***	21.7441
log(E_INDEX_NOM)	-0.1185**	-2.7121
log(Y_RW)	0.0497***	5.4743
log(CPI_E)	0.1565***	5.7278
R^2	0.9985	
DW	2.0558	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Import prices

Dependent variable log(PM)

Variables	Estimated coefficients	t-stats
log(PM(-1))	0.9387***	154.0300
log(Y_RW)	-0.0095***	11.4816
Δ(E_INDEX_REAL)	-0.0004	-1.3100
R^2	0.9990	
DW	1.9867	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Average hourly wages

Dependent variable log(W_HOUR)

Variables	Estimated coefficients	t-stats
log(W_HOUR(-1))	0.9152***	11.1976
log(W_HOUR(-3))	-0.1879***	-3.1618
log(CPI)	0.0401***	2.9947
log(Y)-log(L)	0.1471***	6.2213
UR(-1)	-0.0073***	-4.9766
R^2	0.9967	
DW	2.2465	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Nominal interest rate

Dependent variable R_NOM

Variables	Estimated coefficients	t-stats
R_NOM(-1)	0.6391***	7.9428
log(MS)	-4.5027***	-3.6791
log(Y)	4.5855***	3.6866
Δlog(CPI)	34.1850***	4.5826
Δlog(CPI(-2))	-28.8548***	-4.5000
R^2	0.9370	
DW	2.3065	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Nominal exchange rate

Dependent variable LOG(E_INDEX_NOM)

Variables	Estimated coefficients	t-stats
LOG(E_INDEX_NOM(-1))	1.0932***	8.9948
LOG(E_INDEX_NOM(-2))	-0.2902**	-2.2562
LOG(CPI(-1))-LOG(PM(-1))	-0.1298**	-2.4406
LOG(Y)-LOG(Y_RW)	-0.0668**	-2.0974
D(R_NOM)	0.0086**	2.3420
R^2	0.8848	
DW	2.3004	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Money supply

Dependent variable log(MS)

Variables	Estimated coefficients	t-stats
LOG(MS(-1))	1.3656***	17.0355
LOG(MS(-2))	-0.4752***	-7.0005
LOG(Y(-2))	0.1150***	5.8449
D(R_REAL)	0.0028**	2.5265
INF	-0.0059***	-6.9468
S_RATIO	-0.0046***	-3.6365
R^2	0.9995	
DW	2.1737	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Useful exergy (total)

Dependent variable log(UEX_TOT)

Variables	Estimated coefficients	t-stats
log(UEX_TOT(-1))	0.6516***	5.0110
log(HL(-1))	-0.2894**	-2.4710
log(Y)	0.4439**	2.6993
log(K_GRS(-1))	0.1840	0.9899
R^2	0.9686	
DW	1.8424	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Final energy use (households)

Long-term specification:

Dependent variable log(FEN_C)

Variables	Estimated coefficients	t-stats
Constant	2.6971**	2.2081
log(P_EN_C)	-0.0510***	-3.1787
log(UEX_TOT)	0.5338***	5.7720
log(HDD)	0.4458***	7.8592
log(W_HOUR)	0.4231***	3.9831
R^2	0.9447	
DW	1.3114	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(FEN_C)

Variables	Estimated coefficients	t-stats
ECT	-0.7035***	-6.4174
Δlog(P_EN_C)	-0.0791***	-2.9893
Δlog(UEX_TOT)	0.4551***	4.8950
Δlog(HDD)	0.4906***	15.4421
Δlog(W_HOUR)	0.5579***	5.6818
R^2	0.9344	
DW	1.8595	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Final energy use (industry)

Long-term specification:

Dependent variable log(FEN_IND)

Variables	Estimated coefficients	t-stats
Constant	8.0083***	5.6905
log(P_EN_IND)	-0.0643***	-4.4075
log(UEX_TOT)	0.3860***	3.0610
log(M)	0.1252**	2.4153
R^2	0.9886	
DW	1.2410	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(FEN_IND)

Variables	Estimated coefficients	t-stats
ECT	-0.6434***	-8.1358
Δlog(P_EN_IND)	-0.0696**	-2.7053
Δlog(UEX_TOT)	0.3999***	3.1416
Δlog(M)	0.0990*	1.6940
R^2	0.8456	
DW	1.7108	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Final energy use (other sectors)

Dependent variable log(FEN_OTH)

Variables	Estimated coefficients	t-stats
log(FEN_OTH(-1))	0.8719***	16.7172
Δlog(P_EN_OTH)	-0.1435***	-5.6028
log(UEX_TOT)	0.1383**	2.4749
time trend	-0.0005**	-2.4504
R^2	0.9936	
DW	1.8639	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Energy prices (households)

Long-term specification:

Dependent variable log(P_EN_C)

Variables	Estimated coefficients	t-stats
Constant	25.4654***	5.2119
log(FEN_C)	-1.9708***	-5.6597
log(CPI)	1.2151***	25.6980
R^2	0.9819	
DW	1.0680	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(P_EN_C)

Variables	Estimated coefficients	t-stats
ECT	-0.1641***	-3.0014
Δlog(P_EN_C(-1))	0.2289***	2.8559
Δlog(FEN_C)	-0.6925***	-7.1379
Δlog(CPI)	0.9193***	8.8672
R^2	0.8577	
DW	2.1802	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Energy prices (industry)

Long-term specification:

Dependent variable log(P_EN_IND)

Variables	Estimated coefficients	t-stats
Constant	17.1322***	2.8149
log(FEN_IND)	-1.3603***	-3.4374
log(CPI)	1.0741***	8.3891
R^2	0.9655	
DW	0.8825	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(P_EN_IND)

Variables	Estimated coefficients	t-stats
ECT	-0.1228***	-2.7734
Δlog(FEN_IND)	-0.4003**	-2.6975
Δlog(CPI)	1.1585***	10.4675
R^2	0.8982	
DW	2.1573	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Energy prices (other sectors)

Long-term specification:

Dependent variable log(P_EN_OTH)

Variables	Estimated coefficients	t-stats
Constant	20.9611***	6.5045
log(FEN_OTH)	-1.6329***	-7.0685
log(CPI)	1.3771***	24.3987
R^2	0.9894	
DW	1.0270	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(P_EN_OTH

Variables	Estimated coefficients	t-stats
ECT	-0.2538**	-2.1823
Δlog(FEN_OTH)	-1.7701***	-4.7371
Δlog(CPI)	1.3635***	11.5710
R^2	0.7230	
DW	2.0468	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

CO2 (territorial perspective)

Long-term specification:

Dependent variable log(CO2_TERR/POP)

Variables	Estimated coefficients	t-stats
Constant	-0.9782***	-3.5973
log(Y/POP)	0.9434***	11.9547
log(PEN/Y)	0.4351***	4.7956
Time trend	-0.0155***	-5.3162
R^2	0.9509	
DW	0.9183	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

Short-term specification:

Dependent variable Δlog(CO2_TERR/POP)

Variables	Estimated coefficients	t-stats
ECT	-0.4796***	-4.9297
Δlog(Y/POP)	0.8265***	9.0195
Δlog(Y(-1)/POP(-1))	-0.1442	-1.6483
Δlog(PEN/Y)	0.6957***	8.5801
Δlog(PEN(-1)/Y(-1))	-0.0990	-1.5583
R^2	0.9146	
DW	1.5931	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

CO2 (consumption perspective)

Long-term specification:

Dependent variable log(CO2_CONS/POP)

Variables	Estimated coefficients	t-stats
log(Y/POP)	0.6167***	5.8081
log(PEN/Y)	0.3006***	3.0986
log(M/POP)	0.4314***	7.8041
Time trend	-0.0232***	-6.8530
R^2	0.9005	
DW	0.9639	

***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

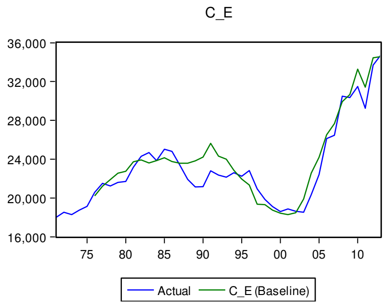
Short-term specification:

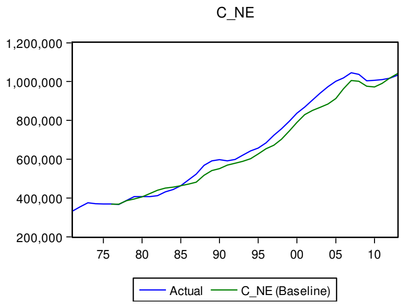
Dependent variable Δlog(CO2_CONS/POP)

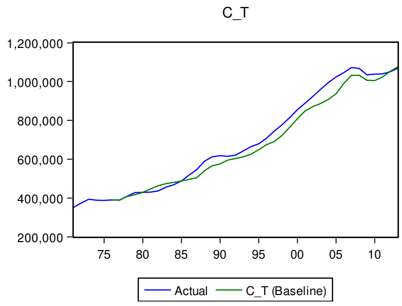
Variables	Estimated coefficients	t-stats
ECT	-0.5040***	-5.0055
Δlog(CO2_CONS(-1)/POP(-1))	0.1444**	2.1819
Δlog(Y/POP)	0.8098***	4.2345
Δlog(PEN/Y)	0.6635***	6.5756
Δlog(M/POP)	0.2140**	2.4476
R^2	0.8657	
DW	1.6582	

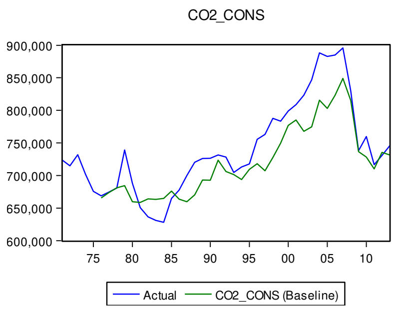
***, **, * Significant at 0.01, 0.05, and 0.10 levels respectively.

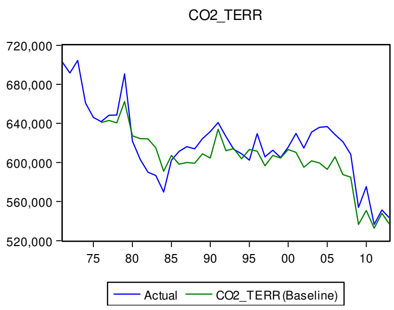
The following graphs show the historical (actual) time-series data and the dynamic fits (baseline) obtained when solving the model. The model is able to replicate the historical behaviour of the endogenous variables.

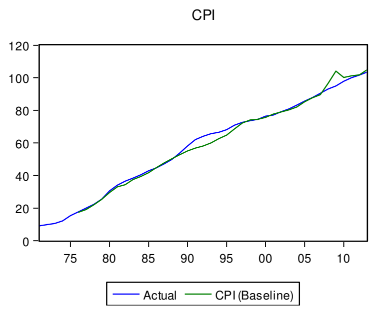


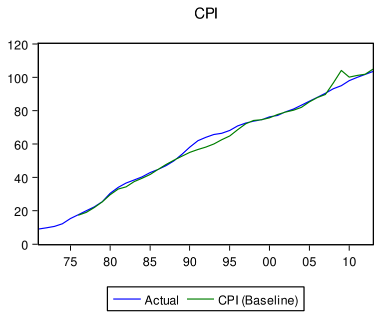


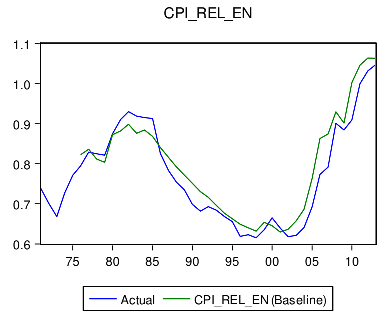


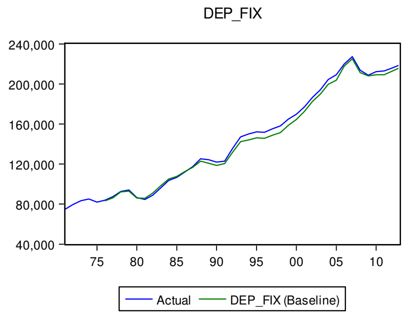


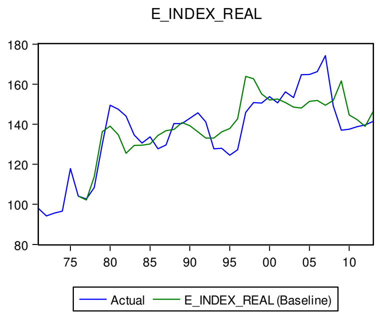


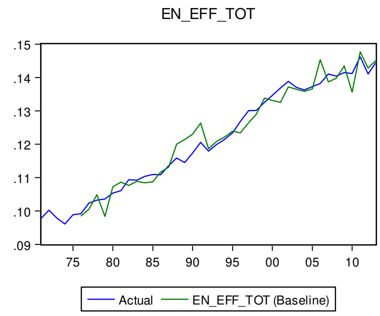


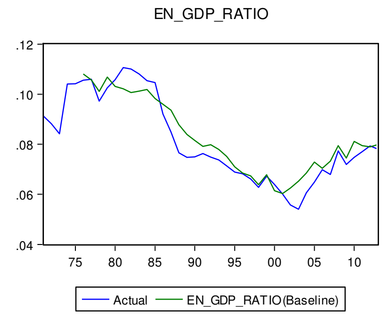

CPI
Actual
CPI (Baseline)

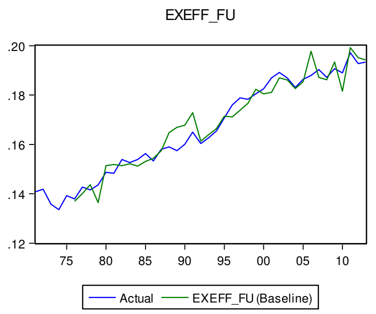

CPI_REL_EN
Actual
CPI_REL_EN (Baseline)

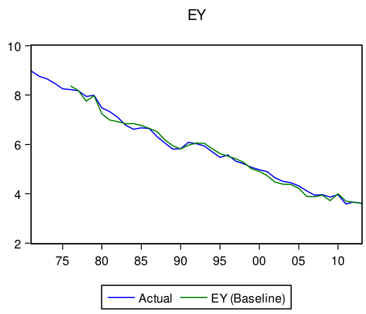

DEP_FIX
Actual
DEP_FIX (Baseline)

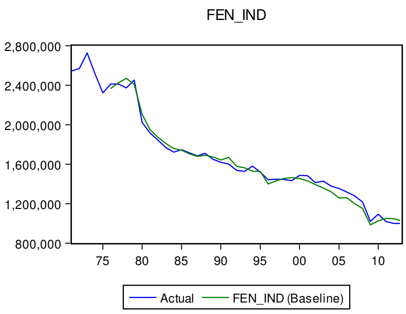

E_INDEX_REAL
Actual
E_INDEX_REAL (Baseline)

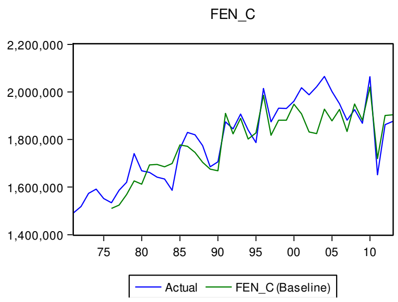

EN_EFF_TOT
Actual
EN_EFF_TOT (Baseline)

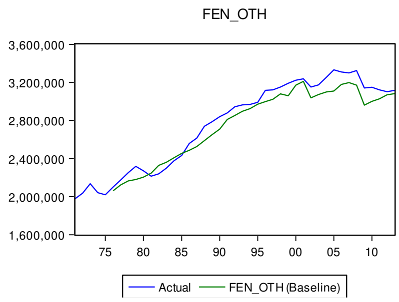

EN_GDP_RATIO
Actual
EN_GDP_RATIO (Baseline)

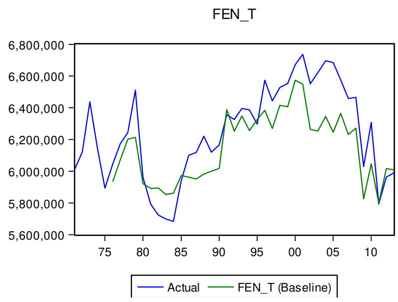

EXEFF_FU
Actual
EXEFF_FU (Baseline)

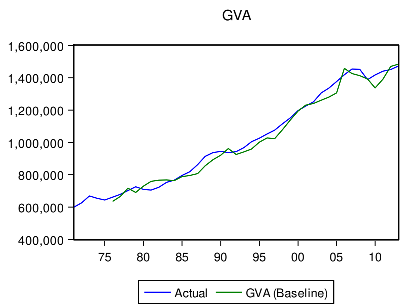

EY
Actual
EY (Baseline)

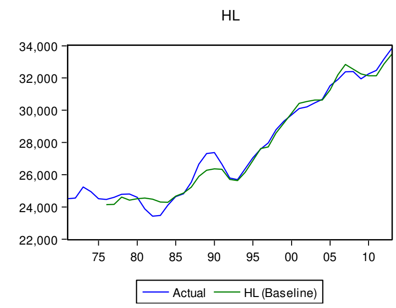

FEN_IND
Actual
FEN_IND (Baseline)

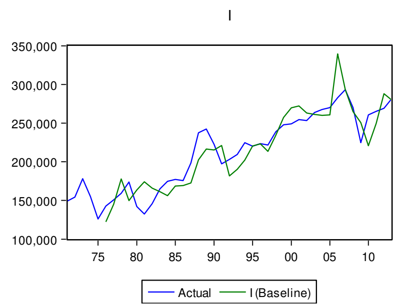

FEN_C
Actual
FEN_C (Baseline)

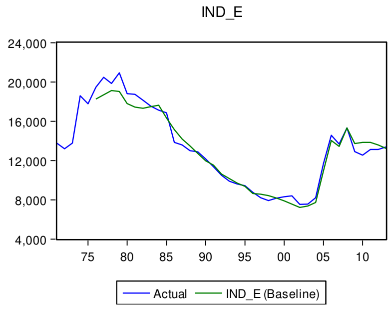

FEN_OTH
Actual
FEN_OTH (Baseline)

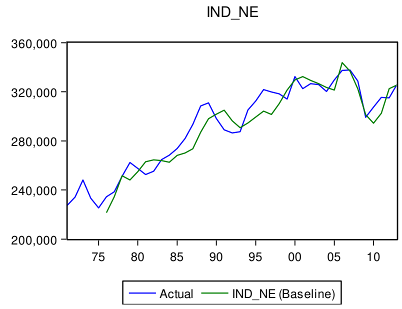

FEN_T
Actual
FEN_T (Baseline)

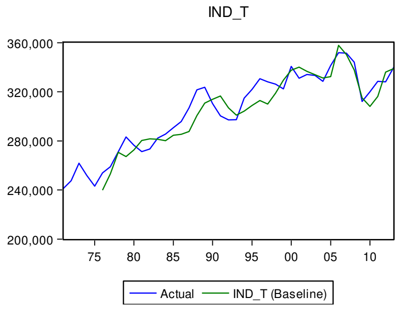

GVA
Actual
GVA (Baseline)

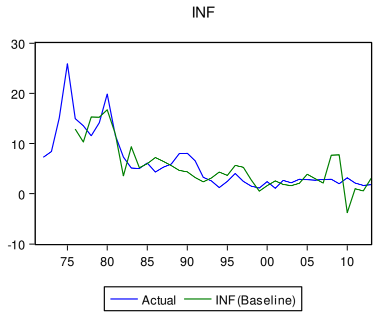

HL
Actual
HL (Baseline)

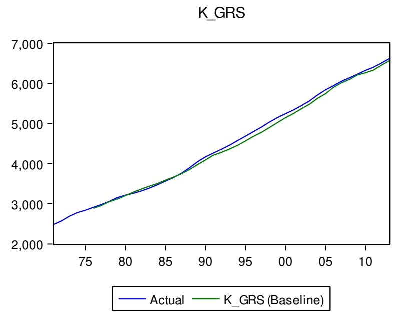

I
Actual
I (Baseline)

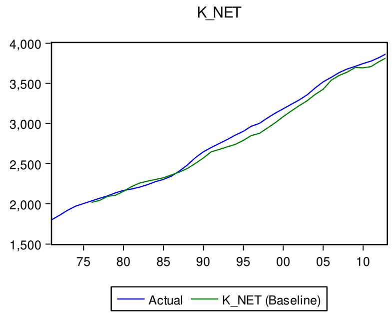

IND_E
24,000
20,000
16,000
12,000
8,000
4,000
75 80 85 90 95 00 05 10
Actual
IND_E (Baseline)

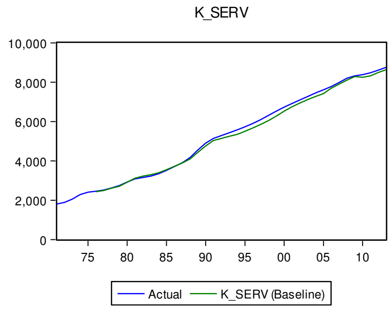

IND_NE
360,000
320,000
280,000
240,000
200,000
75 80 85 90 95 00 05 10
Actual
IND_NE (Baseline)

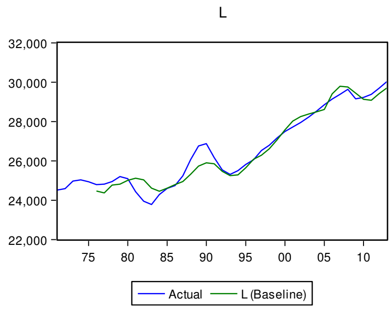

IND_T
360,000
320,000
280,000
240,000
200,000
75 80 85 90 95 00 05 10
Actual
IND_T (Baseline)

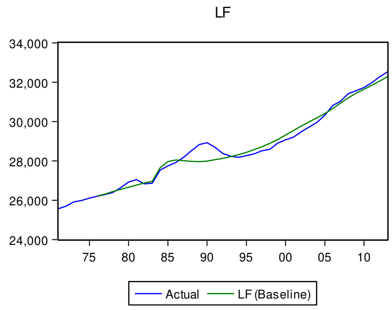

INF
30
20
10
0
-10
75 80 85 90 95 00 05 10
Actual
INF (Baseline)

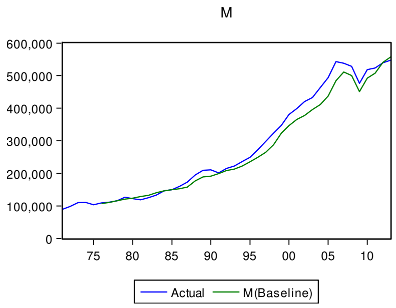

K_GRS
7,000
6,000
5,000
4,000
3,000
2,000
75 80 85 90 95 00 05 10
Actual
K_GRS (Baseline)

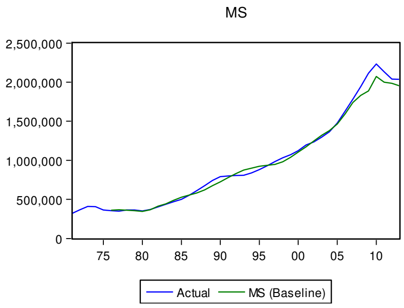

K_NET
4,000
3,500
3,000
2,500
2,000
1,500
75 80 85 90 95 00 05 10
Actual
K_NET (Baseline)

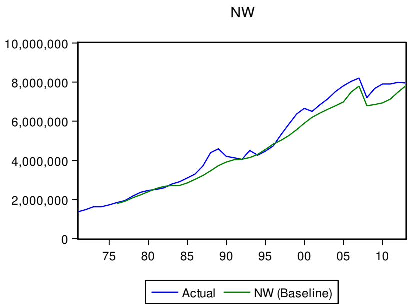

K_SERV
10,000
8,000
6,000
4,000
2,000
0
75 80 85 90 95 00 05 10
Actual
K_SERV (Baseline)

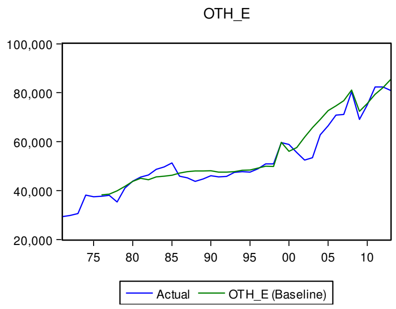

L
32,000
30,000
28,000
26,000
24,000
22,000
75 80 85 90 95 00 05 10
Actual
L (Baseline)

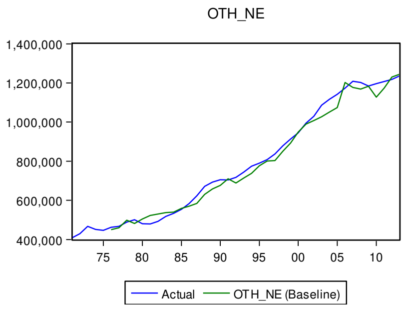

LF
34,000
32,000
30,000
28,000
26,000
24,000
75 80 85 90 95 00 05 10
Actual
LF (Baseline)

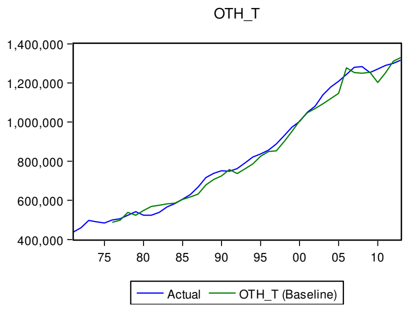

M
600,000
500,000
400,000
300,000
200,000
100,000
0
75 80 85 90 95 00 05 10
Actual
M (Baseline)

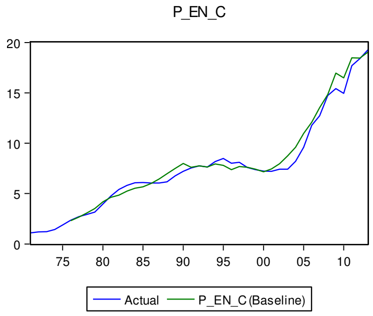

MS
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
75 80 85 90 95 00 05 10
Actual
MS (Baseline)

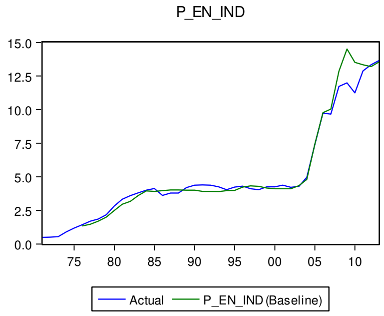

NW
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
75 80 85 90 95 00 05 10
Actual
NW (Baseline)

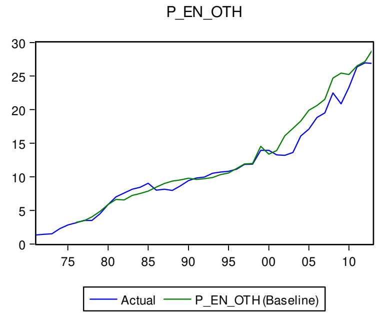

OTH_E
100,000
80,000
60,000
40,000
20,000
75 80 85 90 95 00 05 10
Actual
OTH_E (Baseline)

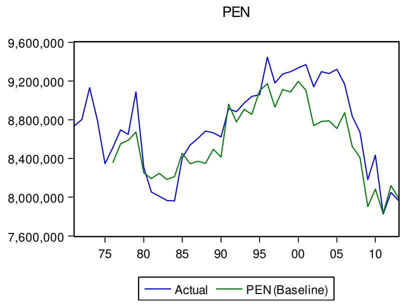

OTH_NE
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
75 80 85 90 95 00 05 10
Actual
OTH_NE (Baseline)

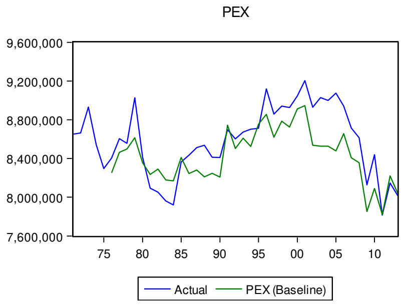

OTH_T
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
75 80 85 90 95 00 05 10
Actual
OTH_T (Baseline)

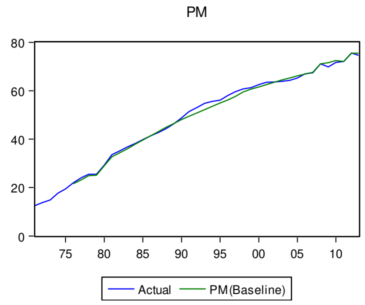

P_EN_C
Actual
P_EN_C (Baseline)

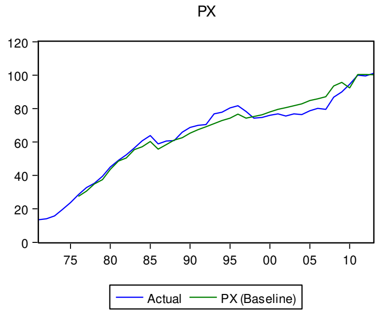

P_EN_IND
Actual
P_EN_IND (Baseline)

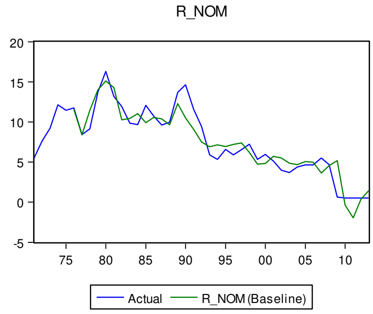

P_EN_OTH
Actual
P_EN_OTH (Baseline)

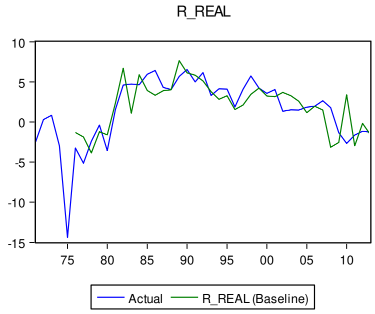

PEN
Actual
PEN (Baseline)

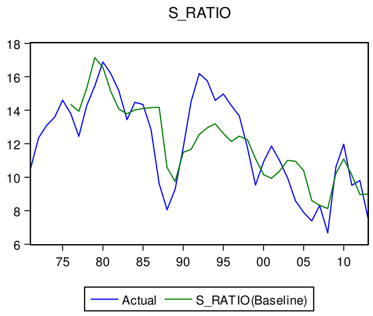

PEX
Actual
PEX (Baseline)

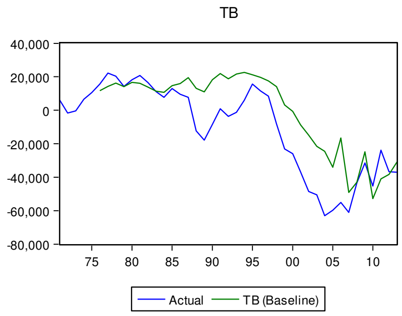

PM
Actual
PM (Baseline)

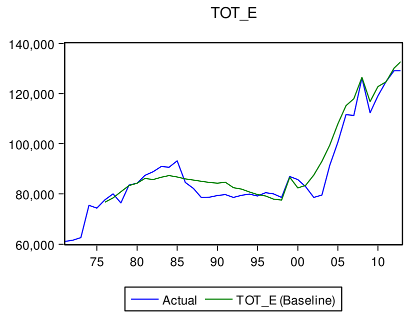

PX
Actual
PX (Baseline)

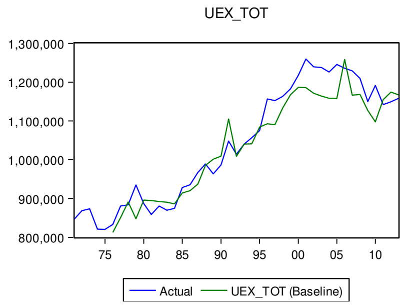

R_NOM
Actual
R_NOM (Baseline)

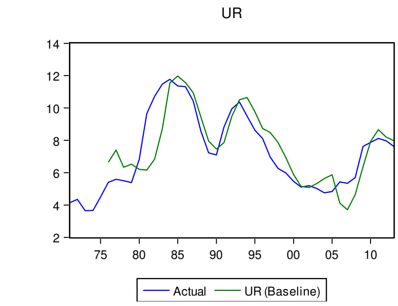

R_REAL
Actual
R_REAL (Baseline)

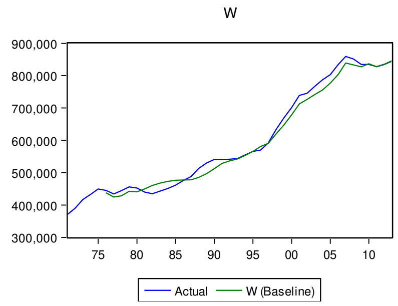

S_RATIO
Actual
S_RATIO (Baseline)

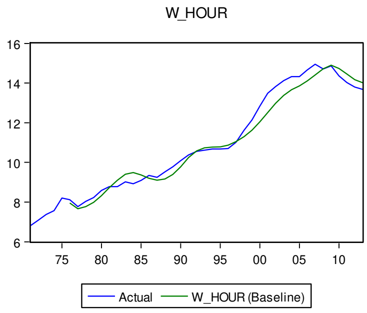

TB
Actual
TB (Baseline)

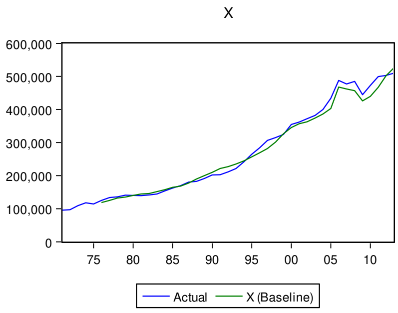

TOT_E
Actual
TOT_E (Baseline)

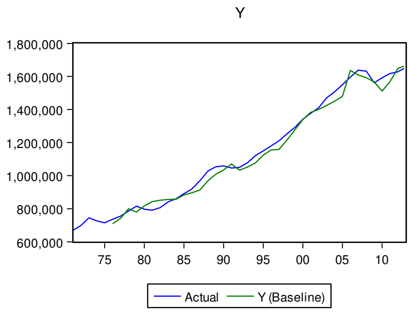

UEX_TOT
Actual
UEX_TOT (Baseline)

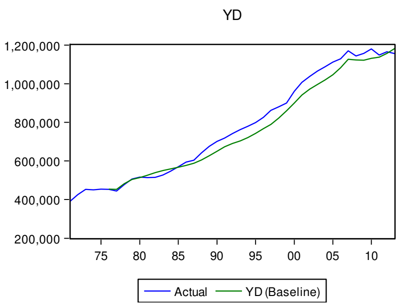

UR
Actual
UR (Baseline)

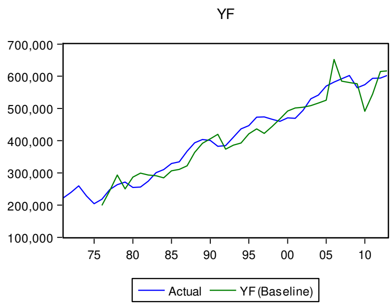

W
Actual
W (Baseline)

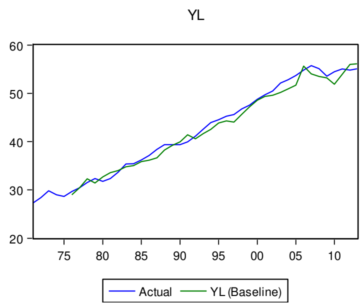

W_HOUR
16
14
12
10
8
6
75 80 85 90 95 00 05 10
Actual
W_HOUR (Baseline)


X
600,000
500,000
400,000
300,000
200,000
100,000
0
75 80 85 90 95 00 05 10
Actual
X (Baseline)


Y
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
75 80 85 90 95 00 05 10
Actual
Y (Baseline)


YD
1,200,000
1,000,000
800,000
600,000
400,000
200,000
75 80 85 90 95 00 05 10
Actual
YD (Baseline)


YF
700,000
600,000
500,000
400,000
300,000
200,000
100,000
75 80 85 90 95 00 05 10
Actual
YF (Baseline)


YL
60
50
40
30
20
75 80 85 90 95 00 05 10
Actual
YL (Baseline)

Appendix D: Data sources used in the MARCO-UK model

Table A4: Data sources used in the MARCO-UK model

Variable	Description	Year coverage	Units	Source
Y	Gross Domestic Product: chained volume measures	1971-2013	£m	ONS
C_T	Household final consumption expenditure: National concept CVM and Final Consumption Expenditure of NPISHs CVM	1971-2013	£m	ONS
G	General Government: Final consumption expenditure CVM	1971-2013	£m	ONS
I	Total Gross Fixed Capital Formation CVM, plus changes in inventories including alignment adjustment, plus acquisitions less disposals of valuables, total economy CVM	1971-2013	£m	ONS
X	Balance of Payments: Trade in Goods & Services: Total exports CVM	1971-2013	£m	ONS
M	Balance of Payments: Imports: Total Trade in Goods & Services CVM	1971-2013	£m	ONS
NW	Total net worth: total non-financial assets plus net financial assets/liabilities	1971-2013	£m	ONS
YD	Real households' disposable income per head, CVM	1971-2013	£	ONS
R_NOM	Annual average of official bank rate	1971-2013	%	Bank of England
Y_RW	World GDP (without UK)	1971-2013	$USD	World Bank
PX	Export deflator	1971-2013	Index	ONS
PM	Import deflator	1971-2013	Index	ONS
E_INDEX_NOM	Exchange rate index 1990=100 new	1971-2013	Index	Bank of England
W	Total compensation of employees	1971-2013	£m	ONS
YF	Gross operating surplus of corporations	1971-2013	£m	ONS
NET_TAX	Taxes on products & production less subsidies	1971-2013	£m	ONS
K_GRS	Gross capital stock	1971-2013	£bn	ONS
K_NET	Net Capital Stock	1971-2013	£bn	ONS
DEP_FIX	Capital Consumption	1970-2013	£m	ONS
CPI	RPI All Items Index: 2011=100	1971-2013	Index	ONS
W_HOUR	Average wage per hour	1971-2013	£	ONS
UR	Unemployment rate: all aged 16 and over	1971-2013	%	ONS
L	In employment: all aged 16+	1971-2016	000's	ONS
LF	Economically Active: all aged 16-64.	1971-2013	000's	ONS
PEN	Primary energy	1971-2013	TJ	DUKES
CO2T	UK CO2 production	1970-2013	tonnes	DEFRA
CO2C	UK CO2 footprint	1970-2013	tonnes	DEFRA
GHGT	UK GHG production	1970-2013	tonnes	DEFRA
GHGC	UK GHG footprint	1970-2013	tonnes	DEFRA
POP	Population	1950-2013	thousands	United Nations Population Division

Variable	Description	Year coverage	Units	Source
MS	M4 (monetary financial institutions' sterling M4 liabilities to private sector)	1971-2013	£m	Bank of England
IND_T	Gross value added (industry)	1971-2013	£m	AMECO
OTH_T	Gross value added (agriculture and services)	1971-2013	£m	AMECO
IND_E	Expenditure on final energy by industry	1971-2013	£m	DUKES 1.1.6
OTH_E	Expenditure on final energy by other sectors	1971-2013	£m	DUKES 1.1.6
C_E	Expenditure on final energy by households	1971-2013	£m	DUKES 1.1.6
C_NE	ABJR (Household final consumption expenditure :National concept CVM SA)	1971 - 2013 (2016)	£m	ONS
GVA	Gross Value Added (Average) at basic prices	1971-2013	£m	ONS
NET_TAX	Total adjustment to basic prices	1971-2013	£	ONS
CPI_E	CPI INDEX: Energy 2015=100	1971-2013	Index	ONS
FEN_T	Final energy use (total)	1971-2013	TJ	DUKES
FEN_IND	Final energy use (industry)	1971-2013	TJ	DUKES
FEN_C	Final energy use (households)	1971-2013	TJ	DUKES
FEN_OTH	Final energy use (other sectors)	1971-2013	TJ	DUKES
P_EN_IND	Energy prices (industry)	1971-2013	£/MJ	DUKES
P_EN_C	Energy prices (households)	1971-2013	£/MJ	DUKES
P_EN_OTH	Energy prices (other sectors)	1971-2013	£/MJ	DUKES
UEX_TOT	Total exergy	1971-2013	TJ	(Brockway et al. 2014)
L_HRS_INDEX	Average annual hours worked by persons engaged	1971-2013	Index	Penn World Tables 9.0 (Feenstra et al. 2015)
L_HC_INDEX	Human capital index, based on years of schooling and returns to education	1971-2013	Index	Penn World Tables 9.0 (Feenstra et al. 2015)
K_SERV_INDEX	Capital services index	1971-2013	Index	Penn World Tables 9.0 (Feenstra et al. 2015)
HDD	Heating degree days	1971-2013	Number of days in a year	(Palmer & Cooper 2013)

Appendix E: List of all variables in MARCO-UK

Table A5: List of variables in the MARCO-UK model

Endogenous variables	
CPI_t	Consumer price index
CPI_E_t	Energy price index
$CPI\_REL\_EN_t$	Ratio of energy price index to CPI
C_T_t	Aggregate consumption
CE_t	Household expenditure on energy goods
CNE_t	Household expenditure on non-energy goods
DEP_FIX_t	Depreciation of fixed capital assets
$E\_INDEX\_NOM_t$	Nominal exchange rate (index)
$E\_INDEX\_REAL_t$	Real exchange rate (index)
$EN\_EFF\_TOT_t$	Efficiency of transformation from primary energy to useful exergy
$EN\_GDP\_RATIO_t$	Fraction of energy expenditure in GDP
$EXEFF\_FU_t$	Transformation efficiency from final energy to useful exergy
EY_t	Energy intensity of GDP
FEN_C_t	Final energy consumption by households
FEN_IND_t	Final energy consumption by industry
FEN_OTH_t	Final energy consumption by non-industry sectors
FEN_T_t	Total final energy consumption
GVA_t	Aggregate GVA
HL_t	Quality adjusted human labour
I_t	Investment
IND_E_t	Industry expenditure on energy goods
IND_NE_t	Industry expenditure on non-energy goods
IND_T_t	Total industry expenditure
INF_t	Inflation
K_GRS_t	Gross capital stock
K_NET_t	Net capital stock
K_SERV_t	Capital services
L_t	Employed Labour
LF_t	Available labour force
M_t	Imports
MS_t	Aggregate money supply
NW_t	Net wealth

OTH_E_t	Expenditure by non-industry sectors on energy goods
OTH_NE_t	Expenditure by non-industry sectors on non-energy goods
OTH_T_t	Total expenditure by non-industry sectors
P_EN_t	Total primary energy used
$P\_EN\_C_t$	Energy price index for households
$P\_EN\_IND_t$	Energy price index for industry
$P\_EN\_OTH_t$	Energy price index for non-industry sectors
PEX_t	Primary exergy
PM_t	Price of imports
PX_t	Price of exports
R_NOM_t	Nominal interest rate
R_REAL_t	Real interest rate
S_RATIO_t	Savings ratio
TB_t	Trade balance
UEX_TOT_t	Total useful exergy used
UR_t	Unemployment rate
W_t	Wage income
W_HOUR_t	Hourly wages
X_t	Exports
Y_t	GDP
YD_t	Disposable income
YF_t	Profits
YG_t	Government income (exogenous up to 2013)
Exogenous variables	
DEP_NFIX_t	Total depreciation of non-fixed capital assets
DEP_RATE_t	Depreciation rate of fixed capital assets
$EXEFF\_PF_t$	Transformation efficiency from primary to final exergy
G_t	Government expenditure
HDD_t	Heating degree days
K_RETIRE_t	Amount of capital retired
$K\_serv\_index_t$	Capital services index
$L\_HRS\_INDEX_t$	Average annual hours by employed persons (index)
$L\_HC\_INDEX_t$	Human capital index
NET_TAX_t	Tax adjustment between GDP and GVA
$PEX\_PEN\_RATIO_t$	Ratio between primary exergy and primary energy
POP_t	Population

$Stat1_t$	Statistical difference
$Stat2_t$	Statistical difference
Stat3	Statistical difference
YG_FRACTION	Ratio of government income and GDP in 2013
Y_RW_t	GDP for the rest of the world